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Preparing for a Changing Climate: Potential Consequences of Climate Variability and Change - Southeast

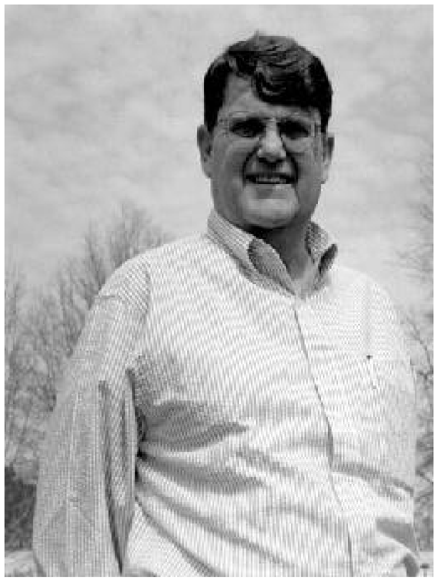
A Report of the Southeast Regional Climate Assessment Team

For the U.S. Global Change Research Program

Sponsored By
National Aeronautics and Space Administration

March 2001

Note: This is a draft report of the findings of the Southeast Regional Climate Assessment Study. It is preliminary in nature and should not be cited or quoted at this time.



This report is dedicated by to the memory of Dr. Ron Ritschard whose energy, enthusiasm and dedication guided the entire assessment effort. The bulk of the report was prepared under Ron's direction prior to his sudden passing in March 2000. He was a friend and mentor to all of those involved in the project and his guidance, humor and warm friendship are greatly missed by us all.

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Executive Summary

This report describes the objectives, methodologies and results of the Southeast Regional Climate Assessment study. The Southeast Assessment is a component of the National Assessment of the Potential Consequences of Climate Variability and Change conducted under the auspices of the US Global Change Research Program. The National Assessment study is made up of a number of regional scale studies that are designed to examine the potential environmental and economic impacts of climate change and to recommend effective coping and adaptation strategies. The regional assessments are a "bottom up" process that involve the participation of interested stakeholders in each region, as well as knowledgeable scientists and leaders in the political and business communities.

The Southeast Regional Assessment process was initiated with a stakeholder workshop in June 1997. At this meeting, key environmental and economic issues were identified for detailed analysis during the assessment study. Using the findings of the workshop and subsequent discussions with stakeholders, it was determined that the Southeast Assessment would focus on issues related to agriculture, forestry, environmental quality (air and water), and severe weather (hurricanes and tornadoes). It should be noted that issues specifically related to coastal processes are being addressed in a separate study.

The Southeast Regional Assessment study was conducted jointly by multidisciplinary teams representing Florida State University, University of Florida, Auburn University, North Carolina State University and University of Alabama in Huntsville. The methodology included economic analyses of present and future markets, biophysical modeling of agricultural and forest ecosystems, projected land conversion between forest and agricultural uses, and environmental analysis of current and predicted air and water quality conditions. Future climate conditions were based on projections from the British Hadley Centre Global Climate Model runs from 1994 to 2100.

According to the Hadley Climate Model, temperatures will increase across the southeast by about 2.3 degrees C on average by the year 2090. The temperature increase is projected to occur in a slightly nonlinear manner, with about a 1degree C increase in the next 30 years (2030). Precipitation is projected to increase slightly (3%) overall in the next 30 years and by about 20% by the end of the century. Precipitation patterns over the region show that precipitation effects will tend to decrease from northeast to southwest. The model also predicts a shift in seasonal precipitation amounts over the region in the 2030 time frame by as much as 10%. Overall, the Hadley Model scenario predicts a slightly warmer and wetter future southeast United States than present. Even though the Hadley Model predicts a less radical climate reaction to future levels of atmospheric CO_2 than do other models, certain aspects of the predicted climate change (particularly the short term seasonal shifts in precipitation) may still have serious ramifications.

Biophysical modeling results based on the Hadley Climate scenario show that agricultural producers in the southeast may benefit slightly due to the increased CO_2, temperatures and moisture over the region. Producers in the Mississippi delta region may benefit less relative to the rest of the southeast. In the forestry sector, productivity of both hardwoods and softwoods are likely to move northward in response to warmer temperatures. However, hardwood forests are expected to benefit more from increases in CO_2 and temperature than are softwoods. In fact, while hardwood productivity is projected to increase by as much as 30-35% over the next century, softwoods may actually decrease slightly overall in the absence of management adaptations. Overall income effects are expected to be positive in most of the region (particularly the coastal plain), but will be less so in the Mississippi delta.

Environmental quality is expected to degrade slightly over the region over the next century. The effects on water quality may be more exacerbated in the first half of the century as precipitation and streamflow are expected to decline by as much as 10% during the spring and early summer months of the year. Water quality impacts will certainly be most pronounced in the Gulf Coast region over this period due to decreased freshwater inflows and rising sea levels. Major urban areas in the southeast are expected to experience increased ozone levels over the next century as a result of increased temperatures. Although the average temperature increases predicted for the region by the Hadley model are relatively small, these temperature increases could be enhanced by the so-called “urban heat island” effect, whereby temperatures are magnified in urban areas due to increased reflected solar radiation and decreased evopotranspiration rates. The enhanced urban heat island may result in negative impacts on human health in terms of respiratory and other heat-related diseases.

A principal component of the Assessment process is the identification of coping strategies that might help the region deal with the potential consequences of climate change. Recommended strategies include changing to more heat resistant crops (certain soybean species, for instance) to maintain agricultural yields, as well as adjustment of planting dates and harvesting schedules to more effectively take advantage of changing temperatures throughout the region. Increased understanding of natural climate variability (e.g., ENSO cycles) would also benefit agricultural producers in scheduling planting and harvesting operations. Forest management improvements include development of more disease resistant and drought tolerant species, as well as improvements in harvest, burning and thinning practices. Knowledge and management of natural disturbances such as fire, hurricane and droughts can also be beneficial in coping with climate changes. Improved management of agricultural and forest ecosystems would also benefit water quality throughout the region. Reduction of effluents, particular nutrients, will be particularly important if water quality conditions are to be maintained or improved under future climate scenarios. Maintenance of adequate riparian zones, particularly in areas where animal wastes are prevalent, will also be a cost effective strategy for protecting water quality. In the air quality arena, the only effective strategy for improvement is in the reduction of emissions through the more efficient use of resources in the transportation and industrial sectors. Improved understanding and prediction of extreme climate events for longer lead times may allow populations to adapt to possible increasing frequencies hurricanes, tornadoes and droughts.

I. SETTING THE STAGE

Chapter 1

Introduction

1.1 Overview

Human activities, primarily burning of fossil fuels and changes in land use, are increasing the atmospheric concentrations of greenhouse gases, which can alter radiative balances and tend to warm the atmosphere (IPCC, 1996). Increases in greenhouse gases are projected to lead to regional changes in temperature, precipitation, and other climatic variables resulting in changes in soil moisture, runoff, mean sea level, and the prospects for more severe climatic events (IPCC, 1996). Increased regional-level understanding of environmental changes and the potential economic consequences of climate variability and change is needed to better explain how these phenomena affect each other and to design effective coping and adaptation measures. Achieving this understanding is a priority for the US Global Change Research Program (USGCRP), which is sponsoring the US National Assessment of the Potential Consequences of Climate Variability and Change.

1.2 The Nation and the National Process

The US National Assessment consists of three major components: assessments of key US regions (i.e., Southeast, Pacific Northwest, California, etc.), inter-regional assessments of five sectors (agriculture, forests, human health, water resources, and coastal areas) and a national overview. These assessments will focus on a process that comes from the bottom up (i.e., participatory stakeholder involvement), is science-based, relevant to societal decision-making, publicly credible, and has adequate communication mechanisms.

The overall goal of the National Assessment process is to analyze and evaluate what is known about the potential consequences of climate variability and change for the nation in the context of other pressures on the public, the environment, and the nation's resources. Furthermore, the assessment is organized to establish and maintain a continuing, interactive dialogue within the region among interested groups and individuals engaged in exploring the challenges and opportunities of climate variability and change. For more details about the national process, see the National Assessment homepage (http://www.nacc.usgcrp.gov).

1.3 The Region and the Regional Process

The Southeast Regional Assessment, sponsored by the National Aeronautics and Space Administration (NASA), US Geological Survey (USGS), and National Oceanic and Atmospheric Administration (NOAA), was initiated through a workshop held in June 1997. The overall purpose of this scoping workshop was to examine the impacts of climate variability and potential vulnerability to future climate change on various economic sectors, with an emphasis on water resources. Seven key economic sectors were evaluated at the workshop by a mix of scientists and regional stakeholders from the public and private sectors. The sectors considered at the workshop were agriculture and forests, coastal and fisheries, extreme events, parks and public lands, science education, urban areas and human health, and water resources. Each sector addressed the following four questions:

- What current environmental stresses and issues form the backdrop for potential additional impacts of climate change?
- How might current climate variability and change exacerbate or ameliorate these existing problems and what new problems and issues might arise?
- What are the priority research and information needs that can better prepare the public and policy makers for reaching informed decisions related to climate variability and change?
- What coping and adaptation options exist that can build resilience to current environmental stresses, and also possibly lessen the impacts of climate change?

The responses to these questions served as points for discussion within the sectors and as the major output of the workshop. The full set of findings and recommendations from the Southeast Regional workshop are documented elsewhere (Ritschard and O'Brien, 1997). Using the findings of the workshop and subsequent meetings with stakeholders of the Southeast, the regional assessment focused on issues related to agriculture, forests, environmental quality (air and water quality), and the crosscutting implications of water resources. The assessment involves the identification of potential impacts and benefits as well as possible coping and adaptation strategies that can be implemented to relieve negative impacts.

To address the interrelated topics of extreme climate, water resources, land use change, and environmental quality in the context of sustainable agriculture and forest productivity, a multidisciplinary assessment team of experts was assembled representing several southeastern universities, federal agencies, and representatives from the stakeholder community (see Appendix A for the regional assessment team members). This team has worked closely with the Southern Technology Council of the Southern Growth Policies Board and other stakeholder groups including representatives from agricultural cooperative extension, forest industry, agribusiness, economic development agencies, and state and local resource managers.

1.4 Goals of the Report

This report was prepared to summarize the results of the assessment. It is organized into four main sections. First, the Southeast region is briefly described including the physical, socioeconomic, and environmental settings. In this section, the current and future stresses are discussed in the absence of climate change as well as a historical perspective of the region's climate and socioeconomic context. The future climate scenarios used in the assessment are also briefly described.

The second section of the report offers a summary of the assessment results for the agriculture and forests sectors, and for environmental quality (air and water) including a historical background and potential future impacts for each sector. We also include a discussion of the response of US hurricane landfalls and tornadoes to seasonal climate variability related to El Niño and La Niña events.

In the next section, adapation options in each sector are included that might help to lessen the impacts of climate change. The strategies listed are not meant to be exhaustive, but they do represent some of the key ways to cope with future climate change.

The last section covers additional issues that are important in the Southeast, but were not included in the current assessment. This section provides a summary of information and research needs and other crucial unknowns that should be included in any future climate assessments of the region. A set of Appendices is presented that covers in more detail the assessment approach and methodology, and a more expanded set of results.

II. THE REGION: PAST, PRESENT, AND FUTURE

Chapter 2

Physiography, Environment, Climate and Economy of the Region

2.1 Physical Setting

The Southeast region (Fig. 2.1) represents 15.4% of the land area of the US and 22.6% of its citizenry (US Bureau of the Census, 1994). Although the Southeast has considerable variation in landforms, it is possible to divide it into five fairly distinct land resource regions based on physical geography (Fig. 2.2). The lower third of the low, flat Florida peninsula is a sub-tropical province with unique features such as the Everglades and the Florida Keys. The Coastal Plain, which dominates the region, is a broad band of territory paralleling the Gulf and South Atlantic seacoast from Virginia to Texas, with a deep extension up the lower Mississippi River valley. The Coastal Plain is relatively flat,

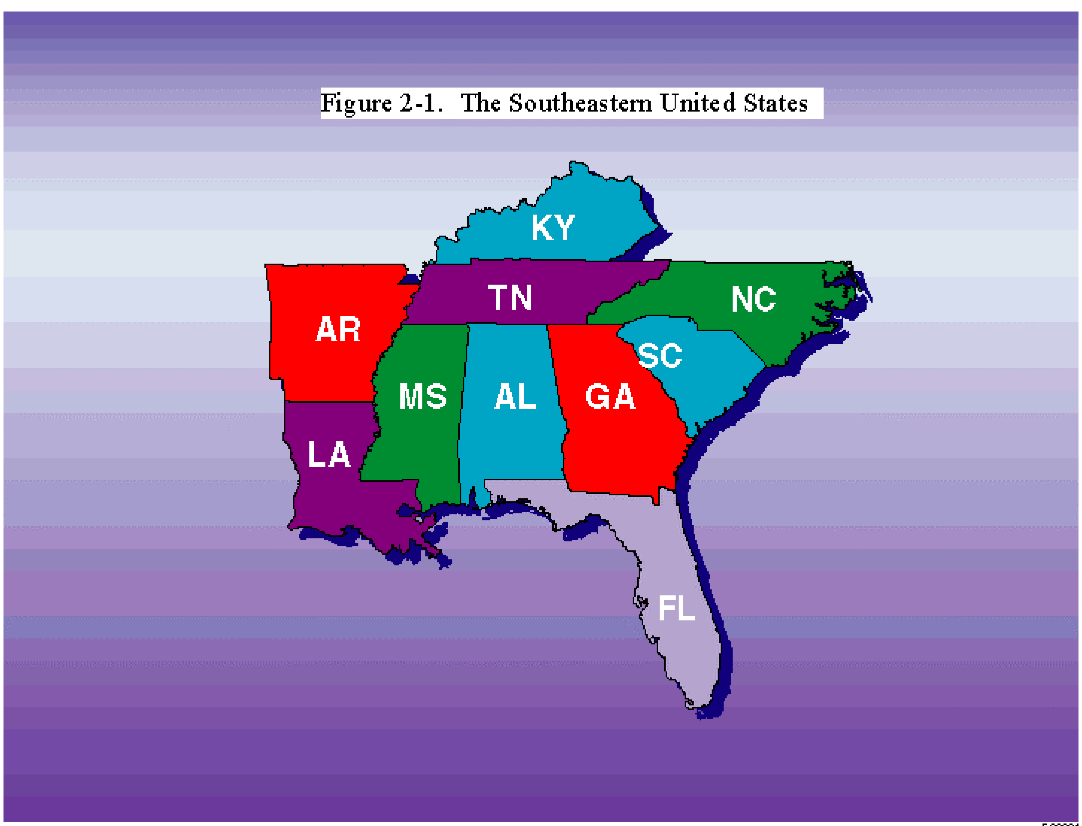
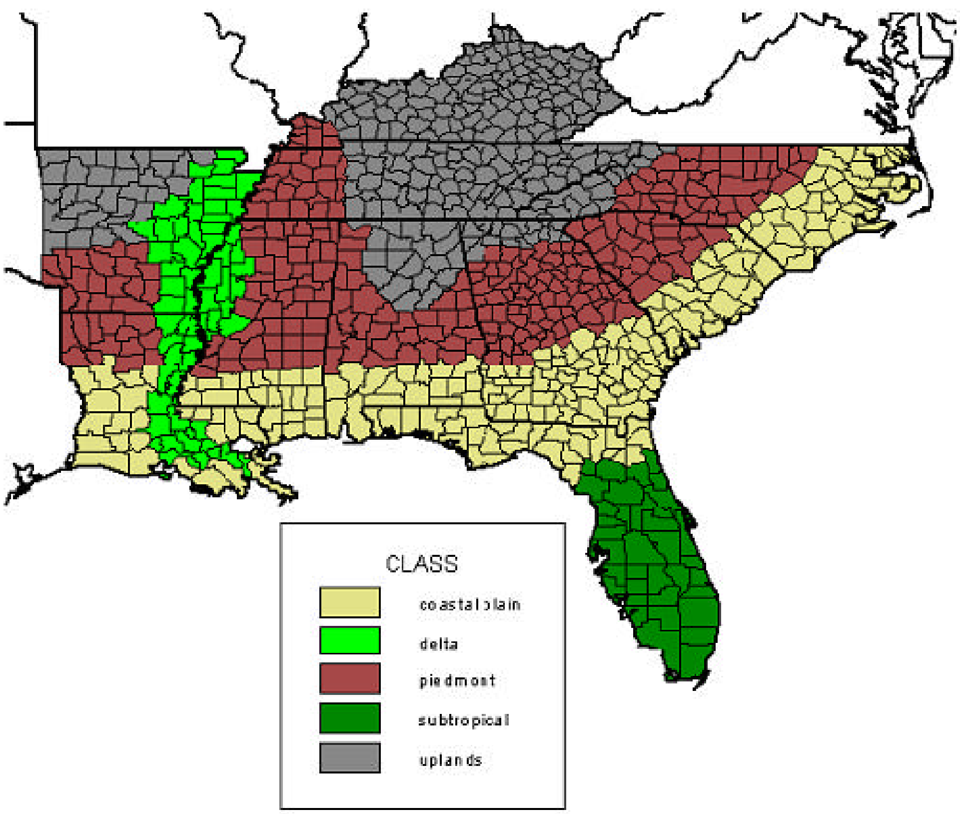


Figure 2-1. The Southeastern United States

with broad, slow-moving streams and sandy or alluvial soils.

The Piedmont is a slightly elevated plateau that begins at the "fall line," where rivers cascade off the eastern edge of the plateau onto the Coastal Plain, and ends at the Appalachian Mountains. This land is rolling to hilly, with many streams. The Highlands comprise the inland mountain regions and include the southernmost Appalachian Mountains in the east and the Ozark and Ouachita Mountains in the west. The Interior Plains stretch into the north-central portion of the region, including parts of Tennessee and Kentucky.

Figure 2- 2. Land Resource Regions



2.2 Socioeconomic Context

The 544,000 square mile southeastern "sunbelt" is one of the fastest growing regions in the US. The southeastern population increased by 21%, more than double the national rate, between 1970 and 1980 and another 11% between 1980 and 1990. Much of the historical population growth from Texas to North Carolina occurred in the 151 counties within the southeastern coastal zone, which are projected to grow another 41% between 2000 and 2025, compared to the projected national average of about 25% (NPA, 1999). However, warming at higher latitudes combined with increased heat stress in the southeastern US may serve to decrease population migration towards the Southeast.

Based on the 1990 Census, about 61% of the Southeast's population is considered urban. The number of farms in the region decreased 80% between 1930 and 1997 (USDA, 1999). The 20th century was one of dramatic transition from an agrarian economy to one based on a combination of natural resources, manufacturing and trade, technology, and tourism. Roughly one half of 1990 employment fell in the categories of manufacturing and wholesale/retail trade, compared with an average of less than 5% in agriculture (US Bureau of the Census, 1994). Prior to 1950, corn and cotton were the most important crops. Today agriculture is more varied; soybean and hay outweigh cotton in acreage harvested and rice has become increasingly important. The Southeast still produces roughly one quarter of the nation's agricultural crops, but timber harvests are more valuable in terms of annual economic impact in most states. Forest products industries were among the top four manufacturing employers in Mississippi, Alabama, North Carolina and Georgia in 1997. The Southeast has become America's "woodbasket," producing about half of America's timber supplies. The region is also responsible for a large portion of the nation's fisheries, poultry, tobacco, oil, natural gas, bauxite, coal, and sulfur production.

According to the 1990 census, 18% of the population of the Southeast region lives below the poverty level. The most poverty-prone areas include the Lower Mississippi River Valley and parts of Appalachia. While certain measurements, such as per capita income, have moved in the direction of the national averages, poverty rates in some areas are as much as two and a half times the national average. Levels of education of the population in some areas also lag behind national standards. Some of the smaller, more remote and geographically isolated areas of the region suffer from a lack of economic opportunities, have significant dependent populations, and lack the public institutions needed to support progressive development (Glasmeier, 1998). These distressed counties present a profound challenge to policy makers concerned about climate change mitigation strategies and issues, particularly in the Appalachian coal-producing and Gulf Coast oil-producing regions.

2.3 Ecological Context

Prior to European settlement, the Southeast was dominated by upland forests, grasslands, and wetlands. Nearly one-third of the region may have been wetland (Dahl, 1990), but by 1990, wetlands had been reduced to about 16% of the southeastern landscape (Hefner, et. al., 1994). A wide range of ecosystem types is presently found in the region, ranging from coastal marshes to high-elevation spruce fir forests. Diversity of both plant and animal species is high compared to other regions considering the extent of landscape alteration that has occurred. On an area basis, the Southeast has relatively high overall species richness indices (Ricketts, et. al., 1999). Vascular plant diversity is second only to Puerto Rico. Tree species richness is greatest in the Southeast, with approximately 180 tree species found in parts of South Carolina and more than 140 tree species identified in most of the remainder of the region.

Forests still dominate parts of the Southeast; the share of forestland in each state averages about 30%. About 20% of the present forests exist as pine plantations. Native longleaf pine was the predominant species in the Coastal Plain in the late 1800s but less than 3 million of the 60 million acres of southeastern longleaf pine remain today (Boyer, 1979). More than 60 species of mammals occur in a relatively small area of the southern Appalachian mountains, while 40 or fewer mammal species are found in the Coastal Plain (Currie, 1991). The region has very high diversity of amphibians and reptiles. Roughly half of the remaining wetlands in the US are located in the Southeast, and more than three-quarters of the nation's annual wetland losses over the past 50 years occurred in the region.

Two types of ecosystem models (biogeochemical and biogeographical) show a wide range of potential changes in vegetation in the Southeast during the 21st century, depending upon the climate scenario selected. One of the biogeographical models (MAPSS) projects significant shifts in major biomes under the Canadian climate scenario, but not under the Hadley climate scenario. Under the Hadley climate scenario, the Southeast mixed forest retains its southern boundaries while expanding west into parts of eastern Oklahoma and Texas, and north into parts of Missouri, West Virginia, Kentucky, and Virginia. Water stress and increased fire disturbance restricts the Southeast forest under the Canadian climate scenario, and large areas of the Southeast are converted to savanna (grasslands with scattered trees and shrubs) and the Southeast forest moves into the northcentral part of the US.

One of the biogeochemistry models (TEM) used in the National Assessment projects large differences in carbon storage for the Southeast depending upon the climate scenario used. Under the Canadian climate model scenario, vegetation is projected to lose up to 20% of its carbon mass by 2030. However, under the Hadley climate scenario the same biogeochemistry model indicates that vegetation will add between 5 and 10% to its carbon mass over the next 30 years. These differences in carbon storage reflect the differences in climate scenario projections for temperature and precipitation that are greatest in the southeastern part of the US (Felzer and Heard, 1999).

Ecological models used in the National Assessment do not simulate species-level response, nor do they simulate land use changes, invasive species impacts, or other influences on ecosystems that cannot be effectively modeled based on historical or empirical evidence, unless the ecological models are linked with other process models, both biological and economic. For example, Harcombe and others (1998) observed that Chinese tallow, a freeze-intolerant non-native tree species, increased dramatically in southeastern Texas over the past few decades. Chinese tallow increased by a factor of 30 between 1981 and 1995, often out-competing native species when canopy gaps form in mesic (medium moisture) and wet sites (Harcombe, et. al., 1998). These kinds of interactions and changes in forest dynamics are difficult to simulate.

Mixed responses among species to fertilization effects of elevated atmospheric CO_2 further confound our ability to model ecosystem structure and productivity. Several studies showed that elevated CO_2 increased photosynthesis rates and improved water use efficiency in many forest species and agricultural crops (Acock, et. al., 1985; Allen, et. al., 1989; Nijs, et. al., 1988). Two reviews of CO_2 exposure studies with deciduous and coniferous species found that increases in growth rates varied widely, but that generally tree growth was stimulated by increases in CO_2 (Eamus and Jarvis, 1989; NCASI, 1995). However, limits on the availability of soil nutrients and water in many natural or semi-natural ecosystems can severely constrain the potential improvement in water use efficiency due to suppressed transpiration induced by enhanced CO_2 levels, thereby offsetting potential gains in productivity (Lockwood, 1999). Temperature, plant pests, air pollution, and light availability could also limit the potential enhancement of growth by elevated CO_2 (NCASI 1995). Hence, one should be very cautious in assuming what the net effects of CO_2 enrichment might be across a region or biome.

2.4 Historical Climate Trends

The Southeast has some of the warmest conditions in the US. However, it is the only region to show widespread but discontinuous cooling periods of 2 to 3.5ºF (1 to 2ºC) over almost the entire area during the past 100 years. Peninsular Florida, North Louisiana, and a few small areas in the Appalachian Mountains have shown a modest warming of around 2°F (1ºC) since 1900. The reason the Southeast temperature record shows a net cooling trend over the past 100 years is that there was a warm period between the 1920s and 1940s, then a significant downward trend through the late 1960s. The mid-1900s cooling trend may have been due to natural variation. Human-caused sulfate aerosol emissions during this period may have also played some role. Sulfate aerosols reflect some sunlight back into space, thereby cooling the atmosphere (Kiehl, 1999). Since 1970, the average annual temperature increased, with the most significant increases occurring during the 1990s. Trends in temperature extremes over the past one hundred years exhibit a decrease of about 5 days in the number of days per year exceeding 90ºF (32.2ºC), and an increase of 6 days in the number of days below freezing over the entire region. However, over the past fifty years the average annual length of the snow season decreased by 4 days.

The Southeast receives more rainfall than any other region. Annual precipitation trends show increases of 20-30% or more over the past 100 years across Mississippi, Arkansas, South Carolina, Tennessee, Alabama, and parts of Louisiana, with mixed changes across most of the remaining area. The southern mountains of North Carolina, the southern tip of Texas, and a couple of other small areas have slightly decreasing trends in annual precipitation. Much of the increase in precipitation was associated with more intense events (rainfall greater than 2 inches or 5 cm per day). A small percentage of the increased precipitation was associated with moderate rainfall events, which are generally beneficial to agriculture and water supply. Analysis of stream flow trends during 1944-1993 showed little change in annual maximum daily discharge, but significant increases in annual median and minimum flows in the lower Mississippi Valley, and decreases in these categories in parts of Georgia and North Carolina (Linns and Slack, 1999). Increased precipitation intensity in extreme events during the next century is suggested by climate models under doubled CO_2 for the US (Mearns, et. al., 1995) and there is evidence that moisture in the atmosphere is increasing over the Caribbean region (Trenberth, 1999). Heavy rains are less efficient (more water runs off into the sea) and are more likely to cause flooding, which is a serious problem in the region.

Trends in wet and dry spells during the 20th century, as indicated by the Palmer Drought Severity Index (PDSI), are spatially consistent with the region's annual precipitation trends, showing a strong tendency to more wet spells in the Gulf Coast states, and a moderate tendency in most other areas. The percentage of the southeastern landscape experiencing "severe wetness" (periods in which the PDSI averages more than +3) increased approximately 10% between 1910 and 1997.

The El Niño/Southern Oscillation (ENSO) phenomenon contributes to variations in temperature and precipitation that complicate longer-term climate change analysis in certain parts of the country, particularly the Southeast. ENSO is an oscillation between warm and cold phases of sea-surface-temperature (SST) in the tropical Pacific Ocean with a cycle period of 3 to 7 years. US climate anomalies (departures from the norm) associated with ENSO extremes vary both in magnitude and spatial distribution. El Niño events (the warm phase of the ENSO phenomenon) are characterized by 2 to 4°F (about 1 to 2ºC) cooler average wintertime air temperatures in the Southeast (Fig. 2.3). During the spring and early summer months, the region returns to near-normal temperatures. Precipitation anomaly patterns following warm events (Fig. 2.4) indicate that Gulf Coast states encounter wetter than normal winters (by about 2-5 cm, or 1 to 2 inches per month). By the spring, the entire eastern seaboard shows increased precipitation. In summer, climate impacts of warm events are more localized; for example, drier conditions are found in eastern coastal regions, and from north Texas to northern Alabama. El Niño events also create upper atmospheric conditions that tend to inhibit Atlantic tropical storm development, resulting in fewer hurricanes, while La Niña events have the opposite effect, resulting in more hurricanes.

Figure 2-3. El Niño Seasonal Temperature Anomalies

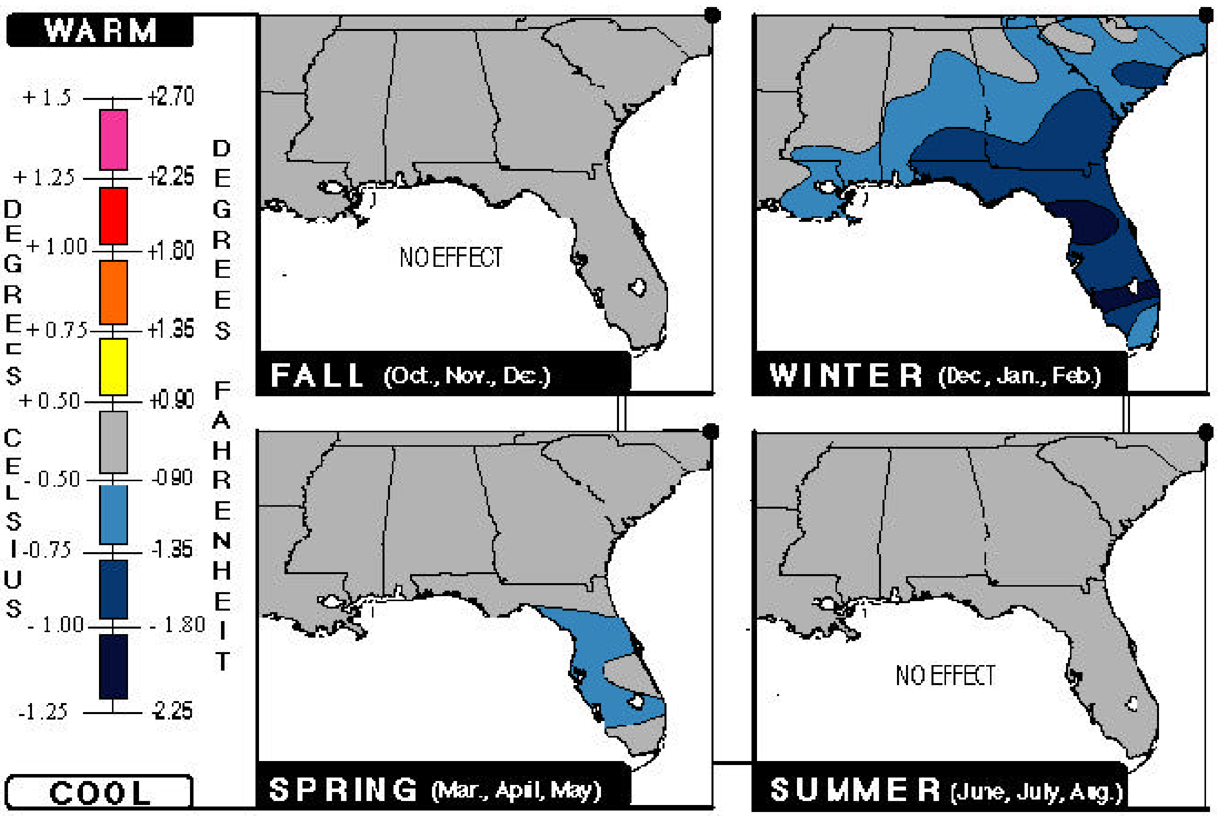
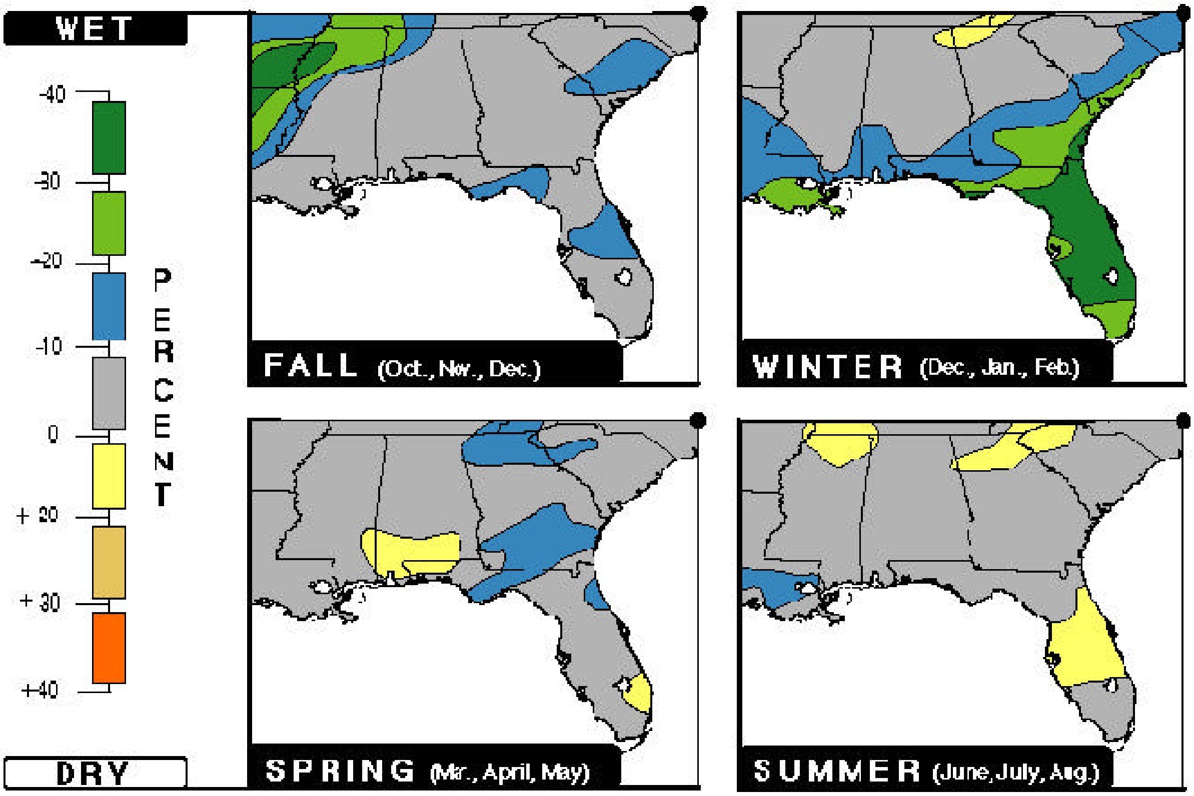


Figure 2-4. **El Niño Seasonal Precipitation Anomalies**



During La Niña events (the cold phase of ENSO), the anomalies are sometimes reversed from those associated with warm events, but not everywhere (Fig. 2.5). Above-average wintertime temperatures are present East of the Mississippi. By spring, the warmer anomalies in the east are focused in the Ohio Valley and northern Florida, Georgia, and South Carolina. Wintertime precipitation patterns associated with cold events show increases (1-2 inches or 2.5-5 cm per month) in the band stretching from northern Mississippi to southwestern Pennsylvania (Fig. 2.6). In the spring, Gulf Coast areas have increased precipitation. In summer, the extreme southern US is colder than normal and greater precipitation is evident in the Southeast. Dry to very dry conditions

Figure 2-5. **La Niña Seasonal Temperature Anomalies**

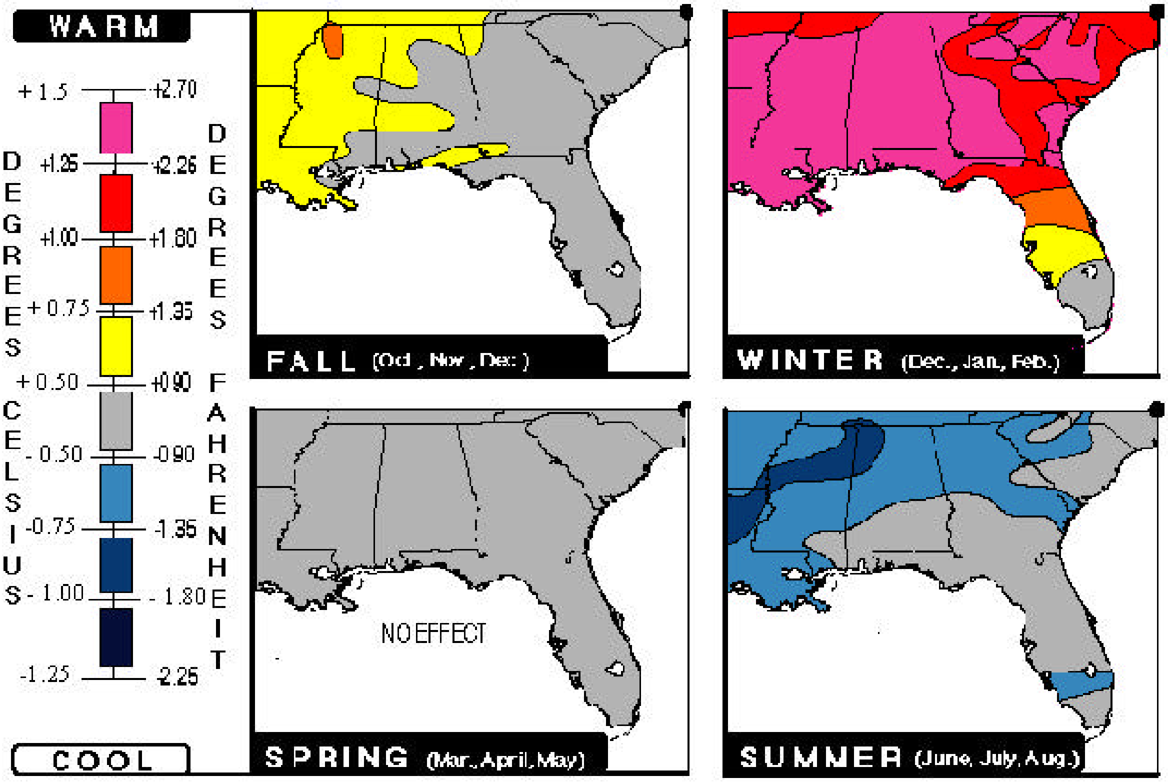
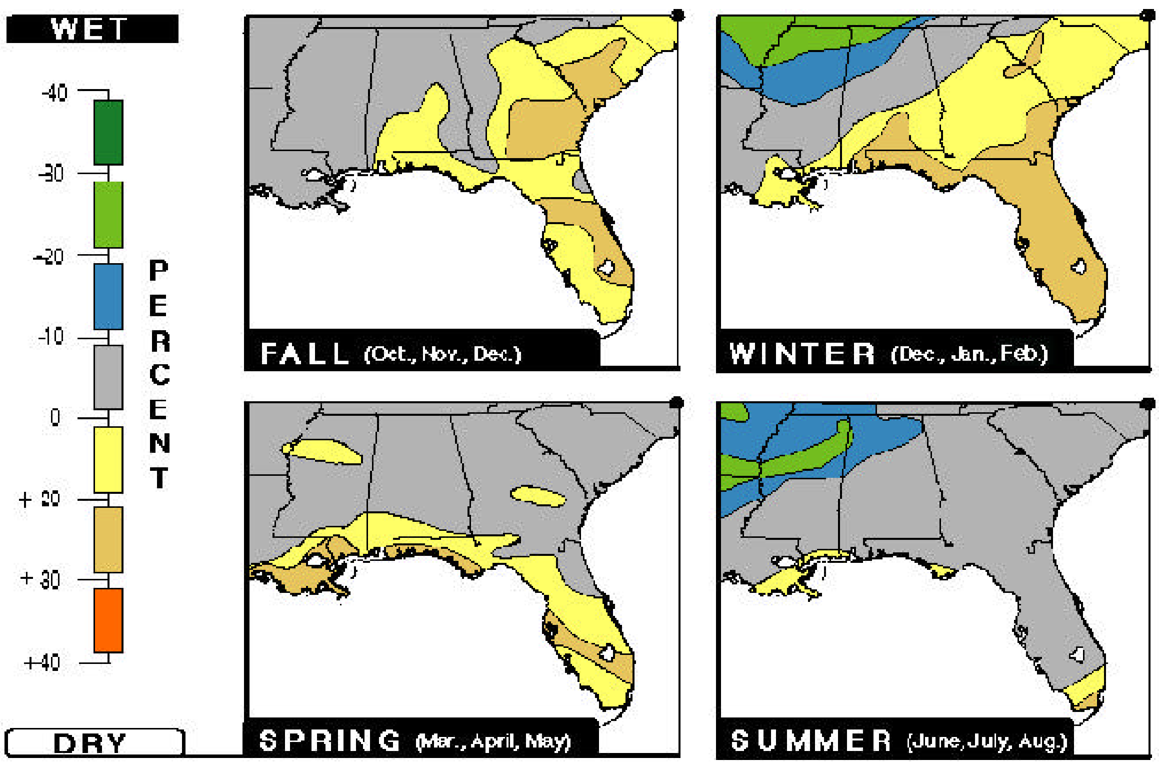


Figure 2-6. **La Niña Seasonal Precipitation Anomalies**



are found in parts of Texas and Louisiana. Thus, as suggested by these results, the climate anomalies associated with opposite phases of ENSO are not in direct opposition. For example, climate anomalies in Florida are nearly opposite (for cold and warm events) while those in many of the midwestern states are of the same sign for both precipitation totals and temperatures during both warm and cold events. Further evidence demonstrates that climate anomalies associated with strong warm events are not amplifications of normal warm events (Rosenberg, et al. 1997).

Chapter 3

Scenarios of Future Climate

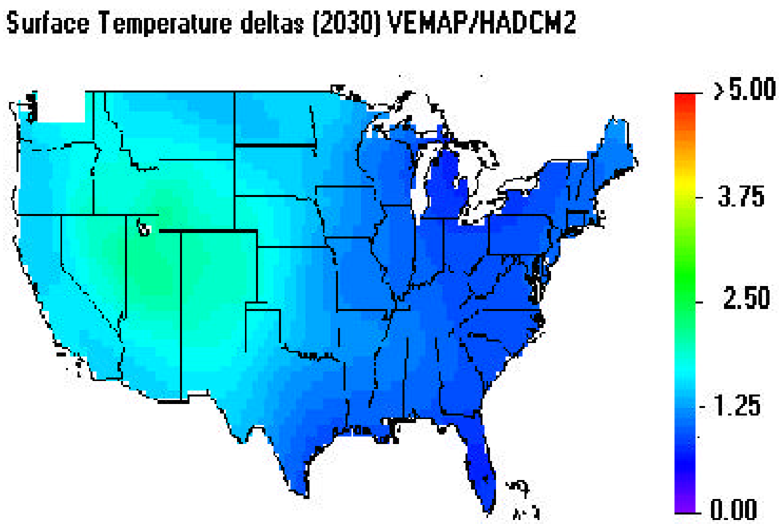
3.1 Climate Data Sets Employed in the Assessment

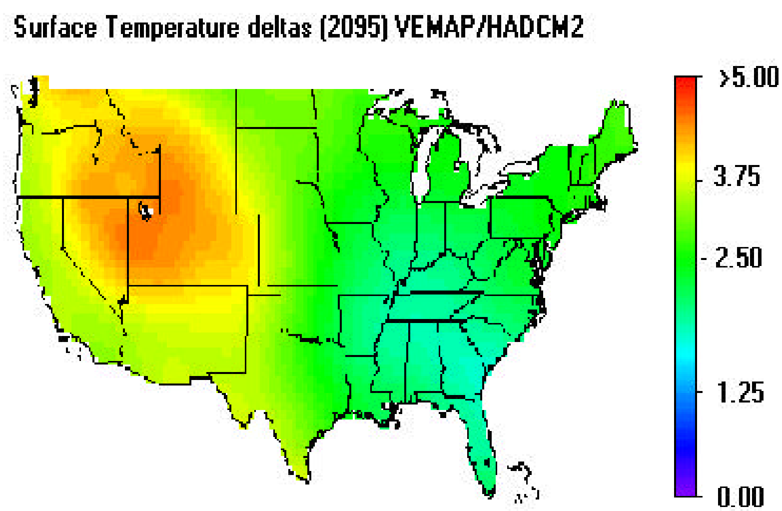
The global climate models (GCMs) used in the National Assessment are all transient, coupled models that include time-varying greenhouse gases and sulfate aerosols (both assumed to increase at the rate of 1% per year) from 1900 to 2100. These climatic conditions for the next century as well as the historical observations from 1895-1995 have been transposed to a 0.5 º gridded format to form the Vegetation-Ecosystem and Analysis Project database known as VEMAP (Kittel et al., 1995; 1997). The two primary GCMs used in the National Assessment are the Hadley Centre (HADCM2, Johns et al. 1997) and Canadian Centre (CGCM1, Boer and Dennis, 1997; Plato et al. 1999).

3.2 Possible Future Climate Conditions for the Southeast

The HADCM2, which was used for most of the analyses covered in this report, projects that by 2030, maximum summer temperatures in the Southeast will increase by about 1.3ºC (2.3ºF) while maximum winter temperatures increase by 0.6ºC (1.1ºF). The increased mean annual temperature of 1ºC (1.8ºF) by 2030 and 2.3ºC (4.1ºF) by 2100 represents a smaller degree of projected warming than for any other region (Fig. 3.1). The smaller simulated warming rate is possibly due to the buffering effects of the oceans, large amounts of surface water for evaporative cooling, and the sulfate aerosol emissions that are prevalent throughout the eastern US. Sulfate aerosols may help explain the mid-20th century cooling trend in parts of the US; however, over the past two decades, sulfate

Figure 3-1. HADLEY CENTRE MODEL RESULTS- TEMPERATURE





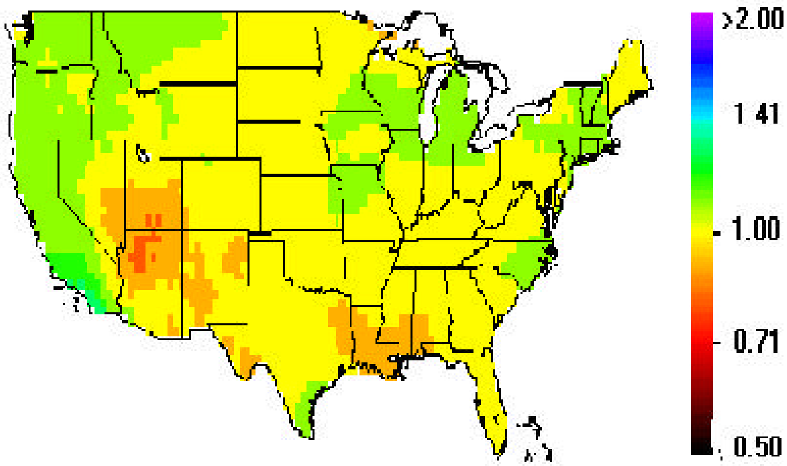
emissions decreased, and the future cooling affect of sulfate aerosols is not expected to be as important due to Clean Air Act restrictions. Although the increase in temperature under the HADCM2 model is small compared to other regions, the resulting increase in the summer heat index by 4-8ºC (8-15ºF) (calculated from monthly maximum temperatures and relative humidity) could seriously affect biological activity and distribution during the 21st century.

According to the Hadley climate scenario, the Southeast will remain the wettest region of the U.S. for the next 100 years (Fig. 3.2). Mean annual precipitation is predicted to increase slightly (3%) by 2030 and by 20% by 2095; most of the increase during the next century is predicted to occur during the summer months. The precipitation changes predicted by HADCM2 model by 2095 are consistent with other parts of the eastern and midwestern U.S.

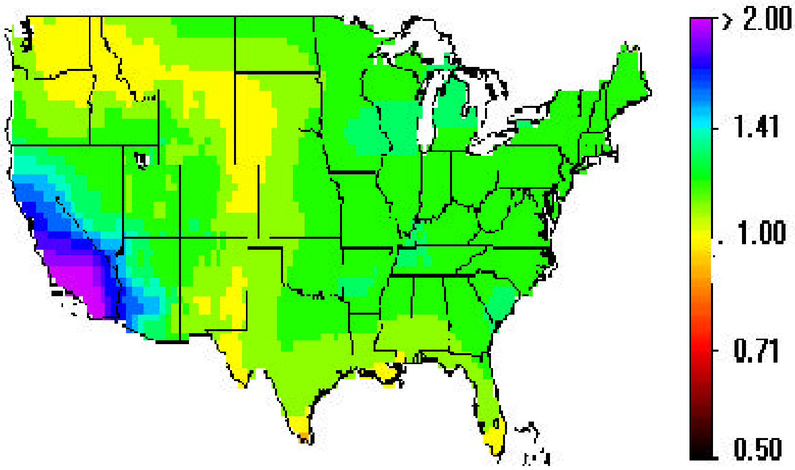
The CGCM1 model produces warmer temperature scenarios for the region than does the Hadley model. The Canadian model simulates an increase in mean annual southeastern temperature of about 1.7ºC (3ºF) by 2030 and 5.5ºC (10ºF) by 2100. In the CGCM1 model, increases in maximum summer temperature are the highest in the nation for both 2030 (2.8ºC; 5°F) and 2100 (6.5ºC; 12°F). Another important difference between the two models for the Southeast lies with the simulated changes in rainfall; CGCM1 simulates less precipitation (20% less by 2030) than present while the HADCM2 simulates more precipitation than present. This difference has important implications for hydrologic impacts on the Southeast, because CGCM1 simulates

Figure 3-2. HADLEY CENTRE MODEL RESULTS- PRECIPITATION

Precipitation Ratios (2030) VEMAP/HADCM2



Precipitation Ratios (2095) VEMAP/HADCM2



decreased soil moisture, while HADCM2 simulates increased soil moisture (Felzer and Heard, 1999).

The Max-Planck-Institut climate model (ECHAM4/OPYC3), one of a few models with sufficient resolution in the tropics to adequately simulate narrow equatorial upwelling and low frequency waves, simulates more frequent El Niño-like conditions and stronger La Niñas under a doubling of CO_2, which is consistent with the Hadley model projections with a doubling of CO_2. The Max-Planck model also suggests that the mean climate in the tropical Pacific region will shift toward a state corresponding to present-day El Niño conditions (Timmermann, et. al., 1999). McGowan, *et al*. (1998) showed that the frequency of warm sea surface events off the western coast of North America increased since 1977, but relationships between this trend and reduced hurricane landfall in the Gulf Coast region have not been established.

Because of problems associated with a georeferencing error, we chose not to consider the CGCM1 estimates in our analysis. To assess temperature and precipitation ranges broader than those found in the HADCM2 model results, a series of sensitivity studies were performed in which temperature and precipitation as well as CO_2 levels were varied in selected locations across the Southeast.

3.3 Importance of Climate Variation in the Southeastern U.S.

Changes in average weather and climate extremes can have important economic implications in the Southeast. There are several reasons why this region is of relatively high interest and concern. First, there is a strong ENSO signal, primarily in the Gulf

Coast states, that results in seasonal and year-to-year variations in temperature and precipitation. Understanding potential future climate change in the context of current natural variability can provide an important contribution to the ongoing discussions of mitigation options. A second consideration is that the Southeast experiences many extreme climate events such as hurricanes, heat waves, tornadoes, ice storms, floods, lightning storms that can cause significant economic losses to industry and local communities. The agriculture and forest sectors are quite vulnerable to climate variability and make substantial contributions to the regional and national economy. Furthermore, air and water quality can both impact and be affected by agricultural and forest sector activities as well as by land use changes.

III. Impacts, Challenges and Opportunities

Chapter 4

Current Status and Stresses

The increasing population of the southeastern US and the changing socioeconomic dynamics from largely rural to largely urban have begun to place stresses on the environment and economy of the region. Any variations due to changing climate must be analyzed in the context of these current stresses. Perhaps foremost among these is the intense competition for water that has developed in some areas of the southeast, particularly among competing users in the Chattahoochee basin located in portions of Georgia, Alabama and Florida. This basin represents a microcosm of the entire region in its evidence of environmental and economic stresses and conflicts. Enhanced urban development in the Atlanta region has placed increased demands on the water resources of the basin and these resources must be allocated between the urban users of Atlanta and other smaller towns, the agricultural producers, and hydropower facilities while maintaining a required navigational capability in the river. Added to this mix is the fact that the river forms the boundary between Georgia and Alabama and ultimately flows into Florida, and the basis for the multi-user and multi-jurisdictional conflicts become clear.

This scenario of rapid urban development, competing agricultural and power water needs, and navigation requirements is being played out throughout the region, albeit to a lesser degree than in the Chattahoochee basin. As a rule, irrigation is used for agricultural purposes less in the southeast than in other major production areas so that the productivity of the region is even more impacted by natural climate variability. The

ENSO cycle is very pronounced in portions of the region so that temperature and rainfall can be quite variable. Agriculture in the southeast is vulnerable not only to seasonal shifts in rainfall and water availability, but also to extreme temperatures, particularly unexpected low temperature occurrences. Extreme shifts in climate, market competition with larger production areas, shifting population from rural to urban, and declining soil quality have been identified as the major sources of stress on the agricultural sector in the southeast (Ritschard and O'Brien, 1997). The fact that the southeast is not the major agricultural production area in the nation means that prices are controlled by factors beyond the region, and this fact, combined with the vulnerability to natural climate variation (wet/dry periods) makes farming in the region a financially hazardous occupation. The average size of farms in the region is much smaller than in the mid-west so that marginal economics controls, and large scale improvements such as installation of irrigation systems are often not possible.

Some of the same factors that affect agriculture in the southeast also impact the forest sector in the region due to the connection between the two economies. While forests cover almost sixty percent of the land area of the region, much of this coverage is by species that are not economically productive (USFS, 1988). Over the past two decades the total amount of forest land has remained about the same; however the quality of the acreage has not remained stable as much forest land has been cleared for urban development and these acres have been replaced by natural reforestation of abandoned agricultural land. Thus, the economic and environmental stresses due to rapid urban development in the region are also important to the forest sector. For example, it has been estimated that the area around Atlanta, GA has lost 350,000 acres of forest cover since 1973 to the expansion of the city (Wade, 2000).

Over ninety percent of the forest acreage in the southeast is privately owned and most of this is in the hands of non-industrial owners (Moulton and Birch, 1995). Stresses faced by the managers of these lands include those due to urban development, droughts, insect infestations, disease and fires. It is important to note that the source of most of these stresses (with the exception of urban development) is related to climate variability so that the forest economy of the region is ultimately as climate sensitive as the agricultural economy. Changes in the climate of the region, whether leading to wetter conditions, or hotter and drier conditions will lead to significant changes in the vulnerability of the forest lands to disease, insects and forest fires. For example, during the drought of 1997-98, over 500,000 acres of forest were destroyed by fire in Florida.

The water quality of the region is also somewhat related to climate variability as well as human activities. Nonpoint pollution sources are perhaps the major influence on the water quality along with salt water intrusion in the coastal plain (Ritschard and O'brien, 1997). High nutrient loadings from agricultural practices represent one of the primary stresses on the water quality of the southeast (Cruise, *et al*., 1999). The nutrient content of the streams tend to be closely related to the streamflow so that nitrogen and phosphorus loads are greater during periods of high flow. However, the results of these loadings may be more evident during periods of low flow when dissolved oxygen (DO) levels may be more impaired (Mulholland, *et al*., 1997). Low DO levels associated with algal blooms during dry conditions lead to significant fish kills in the region on a fairly frequent basis. Thus, the water quality is highly sensitive to streamflow (and thus climate) variability.

Other stresses on the water quality of the southeast include sediment loads and acidic runoff from mining activities, principally in the southern Appalachian region (Ritschard and O'Brien, 1997). Sedimentation and its associated oxygen demand (SOD) can also be associated with other activities in the southeast, including sugar harvesting and rice planting operations in Louisiana, South Carolina and elsewhere. Heavy sediment loads can lead to depleted DO levels in the receiving streams. Sediment particles can also be the means of transport of toxic chemicals such as pesticides and herbicides as well as hydrocarbon products.

The water resources of the southeast are also subject to a stress that may be unique to the region, *i.e.*, elevated water temperatures associated with periods of extreme hot and dry weather and involving releases of cooling water from electrical generating plants. This problem has been particularly evident in the Tennessee basin in recent years, most notably during the 1988-89 drought in the region. Several generating plants in the basin were near critical conditions due to temperature restrictions on the cooling water releases because of the elevated temperature of the river water. Any climate change that would lead to hotter and drier conditions would have the potential to significantly impact the operation of these plants.

The waters of the coastal zone of the southeast, particularly the Gulf Coast region are subject to particular quality stresses associated with sea level rise and salt water intrusion (Ritschard and O'Brien, 1997). Rising local sea levels have resulted in advancing salinity gradients for inland waters of the coastal plain. These increases in salinity have led to the depletion of fresh water vegetation in the region and resulted in the conversion of marsh land to open water at the rate of over 40 mi^2 per year in Louisiana alone (Connor and Day, 1987). Aquifers underlying these areas are the primary source of water in this region and over pumping of these sources has left them vulnerable to salt water intrusion as well. The depletion of the quality of both the surface and ground waters of the coastal zone will almost certainly proceed even in the absence of climate change due to the continued influx of people to the region. The population of the coastal zone of the southeast is projected to increase by over 40% between 2000 and 2025 (NPA, 1999). This influx of people can be expected to increase the stress on the aging water processing and distribution systems of the region, create the need for increased pumping of aquifer sources and increase the rate of salt water intrusion.

The offshore marine waters of the Gulf Coast are also subject to impairment due to the nutrient loading from the fresh water inflows. A large area of oxygen depleted water (known as hypoxia) is known to exist in the northern Gulf and is associated with nitrate fluxes in the Mississippi River inflows (Rabalais, et al., 1999). The source of these nitrates is thought to be the fertilizers applied to agricultural areas in the upper and middle portion of the Mississippi basin. The area of the hypoxic water has increased by about 300% in the past 30 years as nutrient loadings have increased from the basin (Goolsby et al., 1999). This area of oxygen depleted water adversely affects the aquaculture and tourism industries of the region and can be expected to worsen over the course of the next decades as the intensity of agricultural operations increases to keep pace with a growing population.

The air quality of the southeast region is also under increasing stress, primarily due to increased urban development in the region. The 20th century saw a mass migration of population from the rural areas to the cities so that by the 1990 census about 61% of the population was classified as urban. The growth of cities such as Atlanta, Nashville and Houston has led to significant reductions of air quality in these areas, particularly with respect to ozone levels (Wade, 2000). The abundant sunlight during much of the year in the southeast, together with the biogenic sources of volatile organic compounds make the maintenance of ozone levels the major air quality problem in the region. Since the production of ozone is closely related to human activities, such as burning of fossil fuels, the problem can be expected to only worsen over the next few decades as the population of southeastern cities increases. Already, planned development projects in some cities (Birmingham, AL for example) have been rejected due to their potential to exacerbate the air quality problem in the metropolitan region. Ozone production involves chemical reactions in the atmosphere so that it is also tied to climate variables, such as temperature, and thus will be significantly impacted by global climate change.

The regional workshop that was held in Nashville in June, 1997 also identified other climate related stresses on the economics and environment of the region including those related to extreme weather events and human health (Ritschard and O'brien, 1997). Extreme weather events, including floods, droughts, hurricanes and tornadoes impact the stakeholders of the region including those involved in the energy, agriculture, forestry, and tourism sectors, and also impact the environment including the quality of the water resources and ecosystem. Droughts, as well as unexpected spring freezes can result in substantial crop losses in many parts of the southeast. Cotton, corn and soybeans are particularly susceptible to drought conditions in the upper south, while the citrus industry in Florida can be affected by spring freezes. For instance, the damages associated with the drought of 1998 are estimated to exceed $6 billion.

Of course the coastal zone is susceptible to hurricane landfalls and the entire region is impacted by frequent tornado outbreaks in the spring and early summer. Hurricane damages alone have averaged about $15 billion per decade since the 1960's and can be expected to increase in the coming decades as the population and associated development along the coast continues to increase. The total cost of weather related disasters in the southeast in the past two decades exceeds $ 85 billion (NCDC, 1999).

These weather phenomena are known to be related to overall patterns of climate including the ENSO cycle. The relationships between the ENSO cycle and outbreaks of extreme weather, including hurricanes and tornadoes, has only recently become the focus of serious study (Bove, et al., 1998). However, statistically significant relationships between phases of the ENSO cycle (*i.e.*, El Nino and La Nina) and hurricane landfalls and tornado outbreaks in the southeast have been discovered. Therefore, any future climate change that affects the ENSO cycle is bound to impact the number and intensity of hurricanes making landfall in the region as well as the severity of tornado outbreaks.

Human health in the southeastern United States is also related to the climate of the region. For example, periods of extremely hot and dry weather can lead to significant numbers of heat-related deaths (over 200 during the 1998 heat wave alone). Airborne and water-borne infectious diseases such as encephalitis are also well connected to weather. The expansion of major urban areas in the region such as Atlanta, Houston and Nashville have also impacted the health of the population there through the development of urban “heat islands”. These domes of superheated air that develop around major cities in the region can lead to changes in the air quality and local climate of the city and surrounding area and impact the health of the population (Lo, et al., 1997). Impacts include increases in skin cancers, heat stroke and respiratory diseases (Ritschard and O’Brien, 1997).

The current situation in the southeast United States is that the economy and environment of the region are subject to a suite of stresses ranging from moderate (e.g., water quality) to troublesome (e.g., urban air quality) to severe (e.g., coastal processes). Certain sectors of the economy, particularly agriculture, are extremely vulnerable to climate variability and change due to their current status. Most of the region is subject to the impacts of extreme weather outbreaks, particularly hurricanes and tornadoes, that have historically resulted in significant losses of property and life. The following chapters summarize the key findings of the assessment studies by sector. Each chapter begins with a brief summary of the historical perspective, followed by the assessment methodology used, and the potential impacts and opportunities identified through the assessment process.

Chapter 5

Agricultural Assessment Activities

5.1. Historical Perspective

Great agricultural changes have taken place in the Southeast over the past 150 years. In 1849 the South produced more corn than the Midwest; Southeast corn acreage was higher than cotton. Cotton production expanded greatly after the Civil War and by the late 1920s, cotton was more dominant in the South than it was a century before. There was complete mechanization of crop production in the Southeast after World War II and millions of sharecroppers moved to the big cities in the North. This had an important impact not only on labor requirements, but on the whole economic structure of agriculture. There has also been a shifting cropland base in this region as shown in Table 5.1. For example, over the last 50 years soybeans have changed from a minor forage crop to an agricultural staple second only to corn in value of production. As soybeans and rice replaced corn and cotton, farmers chose soils most suitable for the new crops. Drained wetland soils in Arkansas were more productive in soybeans than the old Piedmont soils abandoned by cotton farmers. There has also been a resurgence in cotton production in the last decade or so (Table 5.1).

In terms of agricultural potential, one of the Southeast's most important assets is its potential to expand the acreage devoted to crops beyond the current level. The land from which new cropland can be drawn is currently about evenly divided between pasture and forestland. Although the Southeast could substantially increase acreage devoted to agriculture it fares poorly in terms of native soil fertility. In addition to having low fertility, millions of acres of soils in the Southeast are moderately to severely eroded, the result of decades of continuous corn and cotton production under poor soil management. However, another of the region's agricultural assets is its latitude and proximity to the warm Gulf and Caribbean maritime influence. Overall, the Southeast has a consistent 30- to 90-day growing season advantage over the Corn Belt and the Great Plains. The Southeast has enormous supplies of fresh water in the form of rainfall, surface water flowing through streams and creeks, and groundwater. Water availability gives the Southeast some substantial advantages, including irrigation possibilities that have barely been exploited.

Table 5.1. Principal Crops in the Southeast (thousand acres)
Source: USDA, Census of Agriculture, 1996

Crop	1929	1949	1969	1987	1996
Corn	23,940	20,417	7,869	4,309	5,005
Cotton	23,228	13,031	4,711	3,345	5,931
Peanuts	2,207	2,348	1,046	971	927
Rice	598	1,011	1,194	1,654	2,156
Soybeans	1,321	2,599	13,894	25,645	12,303

The Southeast's mild climate and frequent rainfall predispose the region to an array of agricultural pest problems more serious than anywhere else in the nation. Agricultural pests are an important factor in reducing crop yields or in raising costs. Another consequence of the region's pest problems has been relatively high use of pesticides. Although the Southeast accounts for only 14% of the nation's cultivated cropland, it consumes 43% of the insecticides and 22% of the herbicides used by farmers (USDA Census of Agriculture, 1994).

The southeastern US continues to have a very important agricultural sector that produces many high value crops, such as citrus (oranges and grapefruit), vegetables (tomatoes, green peppers, and celery), strawberries, sugar cane, fruits and nuts, rice and several field crops (peanuts, cotton, corn, tobacco, and soybeans). In 1997, agriculture accounted for over $33 billion in revenue for 8 states in this region (Hansen et al., 1999). This diversity in production is accompanied by equally diverse cropping and farming systems including livestock, agriculture and forestry. The heterogeneous nature of topography, soils, and climate and the relationships between managed a groecosystems and wetlands in coastal regions are unique. Changes in climate could have major impacts on agriculture in this region, varying by crop and location due to the heterogeneity in agricultural production systems, climate, and soil.

5.2 Potential Impacts of Climate Change

5.2.1 Agronomic Impact Studies

Previous studies of the impact of climate change on agriculture in the Southeast have used various crop simulation models to analyze changes in production between current and future climates, both with and without direct effects of elevated CO_2(Curry et al., 1990a and b; Peart et al., 1995; Dhakhwa et al., 1997; Dhakhwa and Campbell, 1998; Alexandrov et al. 2000). The interaction of changes in climate and CO_2 enrichment drive the simulated changes in crop yields and lead to predictions that vary by region. When CO_2 fertilization was included in the simulations, yield losses were reduced, but generally remained significant depending on whether the crop was irrigated or rain fed. Another major drawback of the results reported in previous studies is that they systematically ignored or failed to clearly explain the relationships between crop productivity and weather variables. Without this information it is difficult to understand the results and devise mitigation strategies. They also did not adequately address how the full range of technologies and management techniques available might be employed to mitigate the losses or even derive benefits from a projected climate change. The analyses in this study attempt to improve upon these limitations.

5.2.1.1 Methods

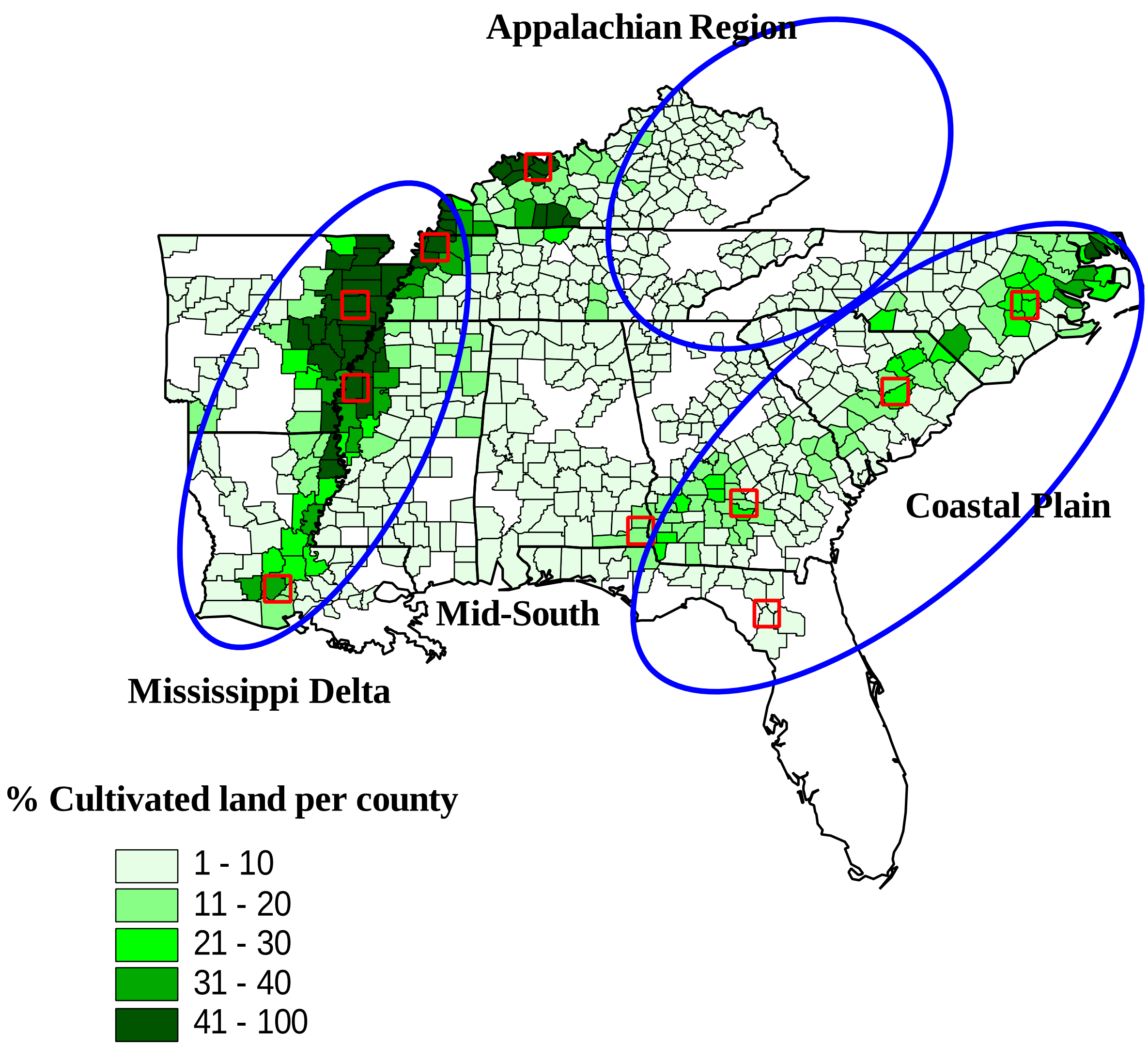
Two families of mechanistic crop simulation models, CROPGRO (for soybean and peanut) and CERES (for maize, wheat, rice and sorghum) in DSSAT V 3.5 (Tsuji et al., 1998), were used to simulate dryland and irrigated production at the field level, using state-and-crop-specific management practices throughout the Southeast. These models take into account local limitations in resource availability (e.g., water, nutrients, temperature) but not other considerations that depend on social and economic response such as soil preparation and pest control. The agricultural assessment used Hadley model scenarios using 20-year periods around 2030s (2021-2040, CO_2 level at 445 ppm) and 2090s (2080-2099, CO_2 level at 680 ppm) in accordance with terms of reference for this study. Weather data at the 0.5º grids was developed by the VEMAP project (Kittel et al., 1997). The baseline climate is derived from a 20-year daily weather data series (1976-1995) and a constant CO_2 level of 360 ppm.

Irrigation requirements were estimated assuming full irrigation capacity. Irrigation was applied as necessary to completely recharge the soil to its field capacity when soil water dropped to a threshold level.. Simulated results of yields, irrigation water, crop duration, etc for each grid cell were analyzed by averaging each scenario over the 20-years of weather data and across a range of currently used planting date and variety combinations. Changes were computed for each scenario relative to the results for current climate conditions, assuming that the agricultural technology and management will neither improve nor adapt. These changes were also divided by simulated values under current climate to obtain percentage changes.

5.2.1.2 Agronomic Sensitivity Analysis

In order to expand the narrow range of climate conditions projected by the Hadley model, a sensitivity analysis was conducted by superimposing a reasonable range of variations in climatic conditions (temperature and rainfall) on the current climate data. The sensitivity analysis was run for 10 regions, one for each of the 10 southeastern states. The representative regions, each measuring 0.5° x 0.5°, were selected on the basis of quantity and diversity of agricultural production, with as many of the study crops as possible being produced on substantial acreage (Fig. 5.1). Changes in climate were generated for the analysis by modifying daily maximum and minimum temperatures and precipitation amounts on each day of the baseline 20-year weather data sets. Temperatures were changed by 1ºC to 5°C and rainfall amounts were changed from -40% to +40% in increments of 20%, creating a total of 25 scenarios. These sensitivity simulations omit other important factors that inevitably influence yields, such as concomitant changes in solar radiation, increased pests and diseases, increased lodging, increased flooding, and loss of plants after emergence. Simulated results were analyzed

Figure 5- 1. Cultivation Intensity, Production Regions (Ovals) and Regions Chosen for Sensitivity and Adaptation analysis. Areas with no significant production are shown in white.



by averaging yields for each combination of temperature, CO_2, and precipitation over the 20-year weather record for each location. The percentage changes in the 10 regions were then averaged to represent overall changes across the Southeast.

5.2.1.3 Adaptation

In the design and implementation of cropping systems, a wide range of adaptations are possible that may maintain or even increase crop yields under climate change conditions. Farmers may respond to changes in changing environmental conditions by modifying planting dates, switching to different cultivars and planting more favorable crops or making other management changes. For the adaptation assessment two temperature and three rainfall change scenarios were assumed. The three rainfall scenarios were –20% (dry), 0% (normal) and +20% (wet) changes in baseline, daily rainfall. Similarly, temperature increases of +1ºC and +2°C were stipulated to represent hotter conditions for the 2030s, and +2ºC (about the same as the Hadley scenario) and +4 °C to represent hotter conditions in the 2090s. For soybeans 5 different generic maturity group (MG) varieties were simulated for each location (the currently used MG plus two earlier and two later MGs). For all other crops, currently grown varieties were simulated together with 1 or 2 later maturing cultivars, to accommodate the projected warmer growing conditions. Seven planting dates at 15 day intervals were simulated for each location, starting with current planting dates, three earlier and three later. For each crop combination, the MGs and planting dates with the highest yield were identified. Optimal changes in crop management and yields were then tabulated.

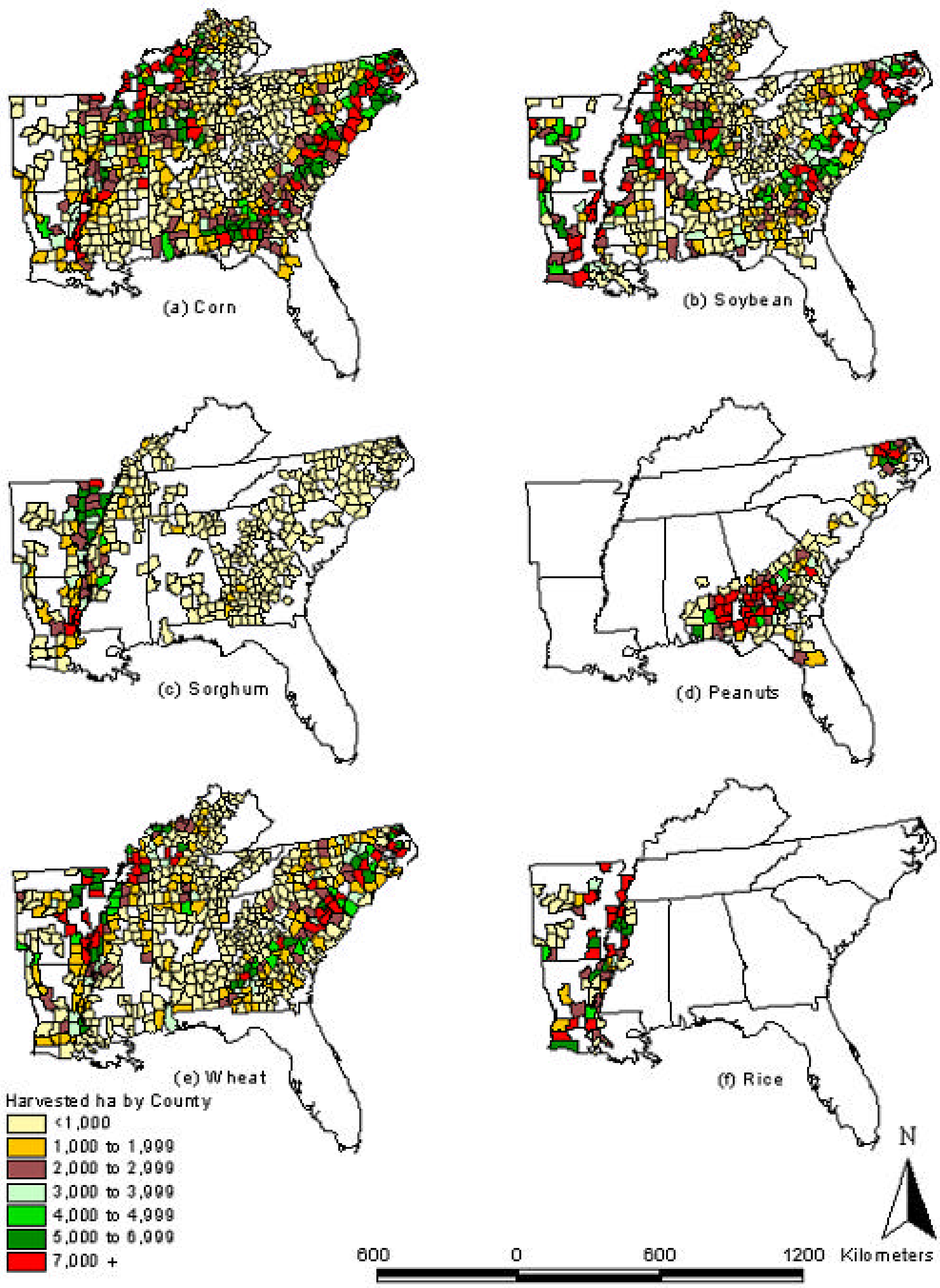
5.2.1.4 Summary of Agronomic Results

The predominant agricultural areas in the Southeast, where 10% or more of the land is devoted to cultivation, are the Coastal Plain and the Mississippi Delta. According to the 1991-95 census at least one of the six crops studied in this assessment is grown in every region of the Southeast, with the exception of large portions of Florida and parts of the Appalachian Region (Fig. 5.2). Annual cropping calendars for the six crops evaluated start with planting of corn in early March, followed by peanuts or rice (mid April), sorghum (May), soybeans (mid May) and wheat in winter (October onward). Consequently, each of the study crops is impacted differently by projected variations in growing season temperature and rainfall.

Many earlier studies simulated effects of climate change by selecting representative locations within the major crop production regions, and scaling the results to generate regional estimates. For the current assessment, we simulated the growth and yield in the contiguous southeastern US assuming that land suitability is not a constraint. Therefore, simulations were done regardless of whether any particular region is currently producing a particular crop, because climate changes could make such production feasible, provided that land is suitable for the crops.

Figures 5.3-5.5 show the 2030 geographic variations in yield under dryland and irrigated conditions along with changes in irrigation for all crops. Yield changes averaged over each state for both dryland and irrigated conditions and the two study periods, 2030s and 2090s, are tabulated in Table 5.2. Projected yields vary throughout the Southeast due to local differences in climate projections (temperature and rainfall) combined with crop specific responses to the assumed CO_2 enrichment. The results

Figure 5- 2. Current Production Areas Represented as Harvested ha During 1991-95.

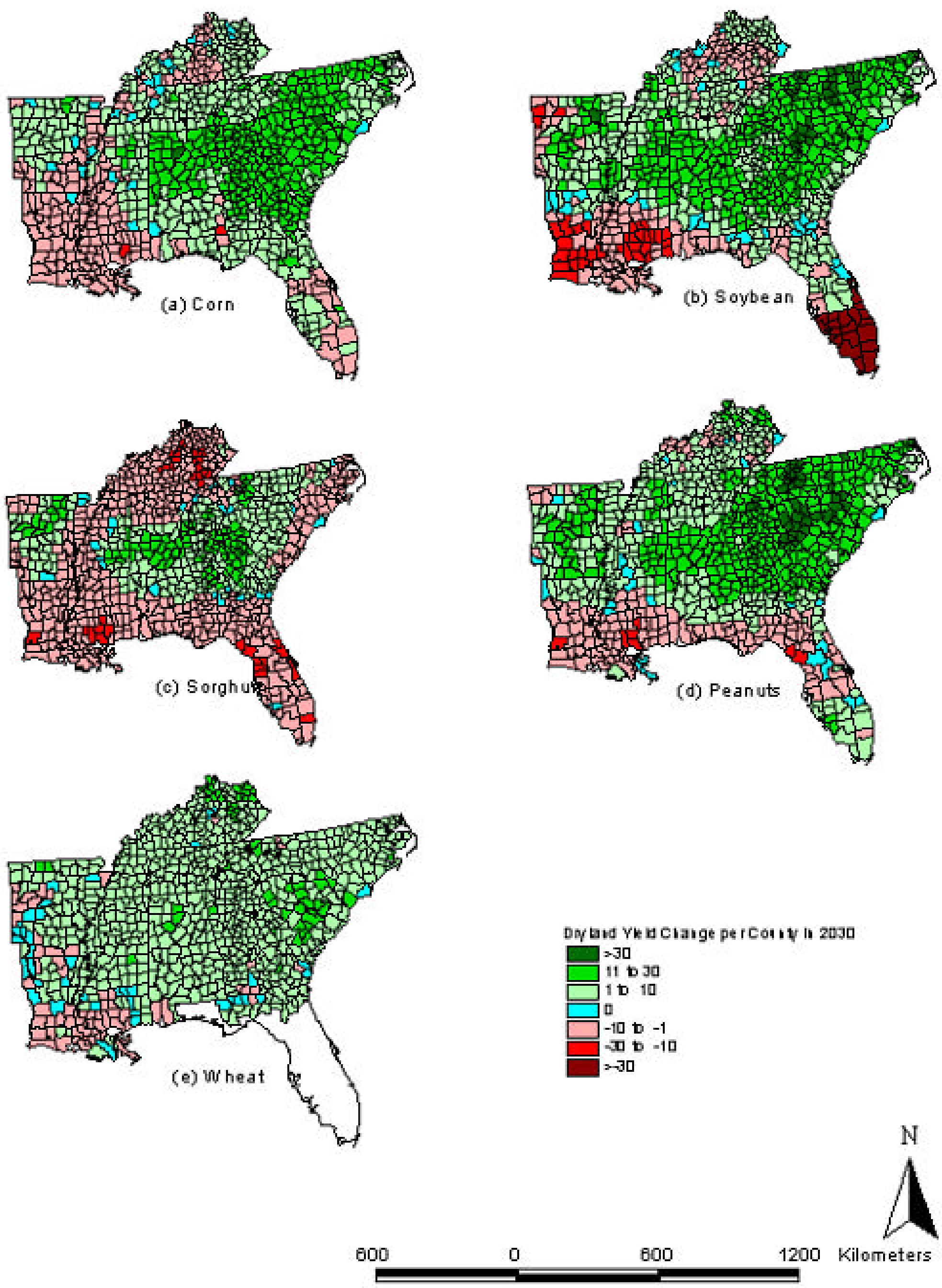


suggest that most regions and crop-irrigation combinations are sensitive to the Hadley scenario climate projections and elevated CO_2 levels. Summary averages for the two most agriculturally-important regions in the Southeast indicate that both dryland and irrigated yields are expected to be impacted positively in the Coastal Plain and negatively in the Mississippi Delta. Impacts of climate change on agricultural yield and water use for each crop are summarized below; the full set of results can obtained from the authors.

Corn – Using the Hadley climate scenarios, simulated dryland corn yield (Figure 5.3a) increased in the major corn producing areas of the Coastal Plain and mid-south by 1-30%. In North Carolina and Georgia, where seasonal rainfall increased by 10-18%, yields increased by 13-15% (Table 5.2). Corn yield decreased up to 10% in Louisiana and large parts of Mississippi, Arkansas, and Kentucky. This was partly because corn matured about 3 days (range 0-6) earlier and rainfall decreased by 5-7% in Louisiana, and Mississippi. For most crops, duration of crop growth or number of days to maturity depends on the total growing degree days that have been accumulated since planting. Because of the higher temperatures, fewer days are required to reach the growing degree days limit for maturity, so the plant will receive less solar energy for photosynthesis during this shorter growing season. Therefore, a shorter growing cycle reduces yield while increased CO_2 fertilization and rainfall boost yields. Decreased frequency of low temperature stress could also contribute to yield increases in the northern fringes of the study region.

Irrigated yield losses are projected to extend into areas where gains had been predicted under dryland conditions (Fig. 5.4a). This response is due to the shortened growing season caused by higher temperatures. Irrigation requirements increase by up to

Figure 5- 3. Changes (%) in Dryland Yield in 2030s



50% in Louisiana, Mississippi, and Florida as a result of a combination of warmer temperatures and lower rainfall. Conversely irrigation requirements are less due to increased rainfall over large parts of the Coastal Plain and mid-south (Fig. 5.5a). These yield trends intensify further by 2090 (Table 5.2), indicating that the yield advantage of irrigated corn should diminish relative to dryland corn as warming increases.

Sorghum- Sorghum is grown largely in the Delta region and in some parts of the Coastal Plain and mid-south. Sorghum yields (Fig. 5.3c) are expected to decrease in the Delta, Tennessee, Kentucky and parts of the Coastal Plain, mostly due to 8-days shorter growing season and lower rainfall in the 2030s under a warm Hadley scenario. However, yields are expected to increase by 1-30% in parts of Alabama , Georgia, South Carolina and North Carolina, because of seasonal rainfall increases of 5-15%. Yields from irrigated sorghum are lower almost everywhere (Fig. 5.4c), even where higher yields are predicted under dryland conditions. This is largely due to shortened growing seasons. Required irrigation increases by up to 50% in Louisiana, Mississippi, and Florida where rainfall decreases, while it decreases over large parts of the Coastal Plain and mid-south (Fig. 5.5c). By the 2030s, sorghum yields are expected to increase 3% and 7%, respectively, in Arkansas and Georgia and decrease 7% and 2% in Louisiana and Mississippi. These four states are currently the top sorghum producers in the Southeast. Irrigated yields decrease by 4-7% in these states over the same period. These trends intensify by 2090. The opposite pattern of yield changes is projected to occur in Kentucky, Tennessee, and South Carolina.

Figure 5- 4. Changes (%) in Irrigated Yield in 2030s

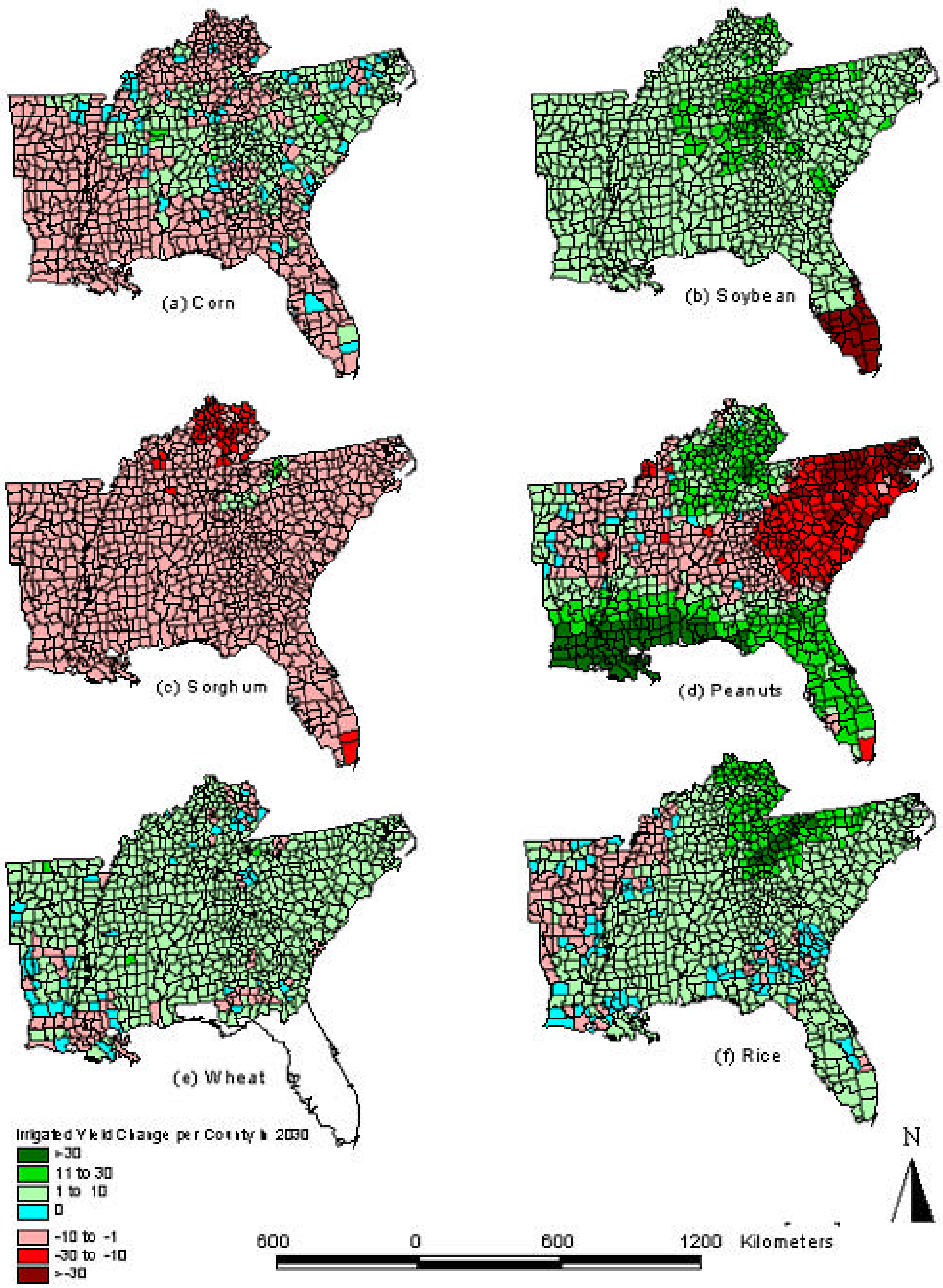
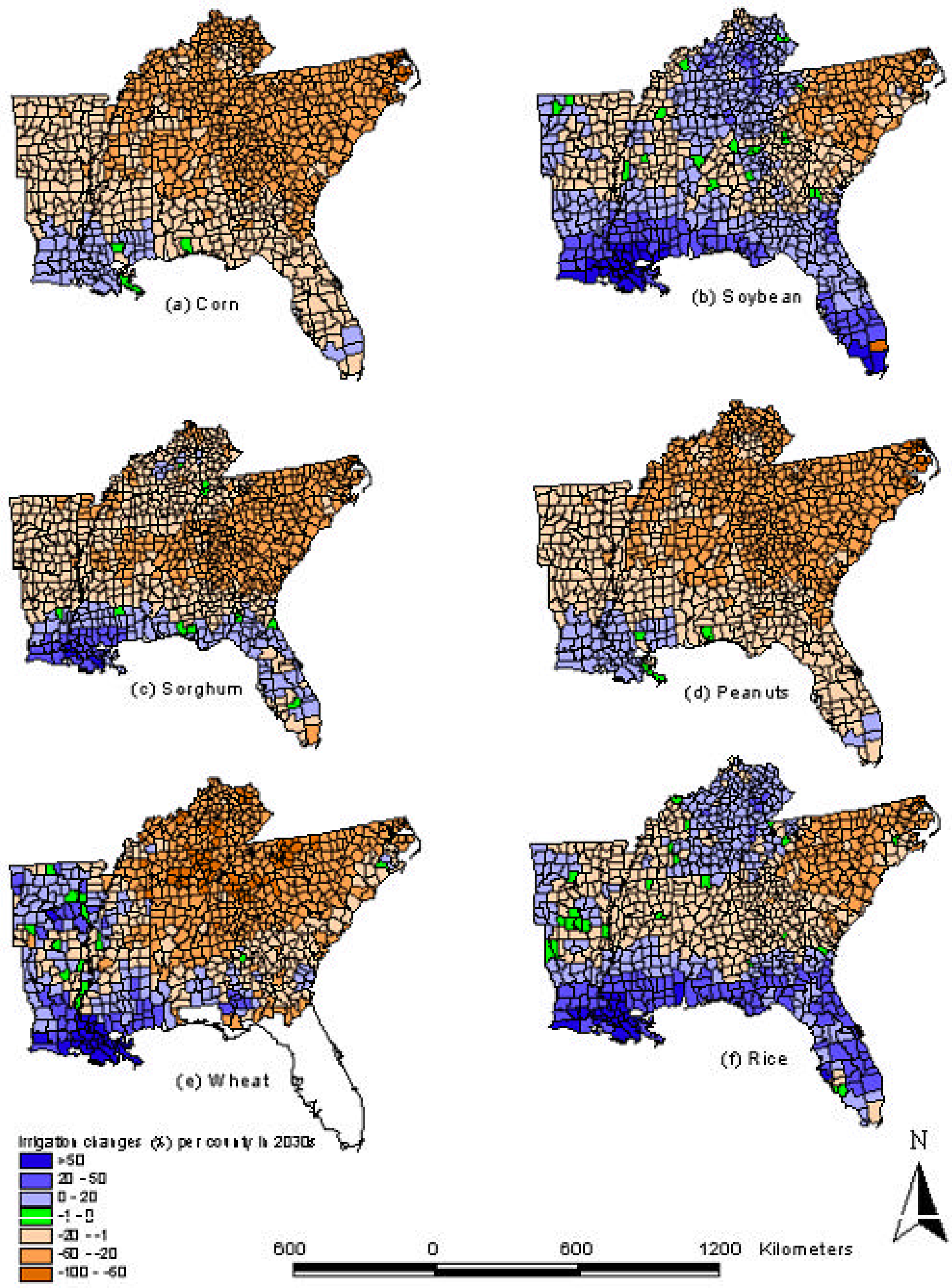


Figure 5-5. Changes (%) in Irrigation Water Use in 2030s



Soybean – Soybean yields are projected to increase by 1-30%, mostly within the Coastal Plain and mid-south (Fig. 5.3b). In parts of North and South Carolina, projected yields increase even more than 30%. Yields also increase in parts of Arkansas and upper Mississippi, where dryland corn and sorghum yields are expected to decrease. This occurs because CO_2 fertilization has an almost three times greater effect on soybean yields than on corn or sorghum. Soybean yields decline more than 10% in the lower Delta and Coastal areas of Louisiana, Mississippi, and Florida where rainfall is projected to decline. Irrigated yields increased 1-10% (Fig. 5.4b) throughout almost all the regions, including those where dryland yield losses are simulated. The projected changes should increase the advantage for irrigated over dryland soybean production, and consequently increase demand for irrigation water, because of decreasing growing season precipitation and higher temperatures which lead to increasing evapotranspiration (Fig. 5.5b). Due to the higher productivity of irrigated soybeans and a lower demand for irrigation water for other crops, irrigated soybean area may expand over time in North and South Carolina. Currently the three-top soybean producing states in the region are Arkansas, North Carolina, and Mississippi, which are expected to record 2-22% increases in dryland yields in 2030s, and 19-57% increases by the 2090s (Table 5.2). If water availability remains at current levels, there is potential to increase irrigated acreage by 8-12% in the 2030s and 11-29% in the 2090s.

Peanuts- Dryland peanut yields are expected to increase throughout the Coastal Plain, mid-south and upper Delta by 11-30% and even more in the Carolinas (Fig. 5.3d). Yields could decrease along the Gulf Coast by 1-10% due to water stress. With increased water demand and higher temperatures, water stress and drought conditions are projected in those areas where rainfall declines. Although increases in atmospheric CO_2 concentrations have been shown to reduce crop water use by increasing leaf stomata resistance, this effect is counteracted by interactive factors during the crop's growing cycle and will not suffice to offset the increases in crop water demanded due to higher temperatures.

Although temperatures are expected to increase throughout the Southeast, increases in rainfall and CO_2 fertilization are expected to increase peanut yields in the Coastal Plain and mid-south regions. Absolute irrigated yields will be lower throughout Carolinas, and Arkansas; northern Mississippi, Alabama and Georgia; western Tennessee, and Kentucky (Fig. 5.4d). However, irrigated peanut production promises up to 25% higher yields in coastal areas. The northern fringes of the Coastal Plain and mid-south should see reductions in the use of irrigation water for peanuts by about 20% (Fig. 5.5d). On the other hand, demand for irrigation water will increase in the lower Mississippi Delta by up to 20%. Projected rainfall decreases in the Delta and Gulf Coast areas contribute to these results.

Table 5.2. Simulated yield changes (%) in dryland and irrigated for 2030s and 2090s compared to the current yields.

		Yield Changes in %																			
		AR		NC		GA		LA		MS		KY		AL		TN		FL		SC	
	Period	Dry	Irr	Dry	Irr	Dry	Irr	Dry	Irr	Dry	Irr	Dry	Irr	Dry	Irr	Dry	Irr	Dry	Irr	Dry	Irr
Corn	2030	2	-3	**13**	**1**	**15**	**1**	-6	-5	0	-3	**1**	**-3**	10	1	**5**	**0**	3	-4	19	2
	2090	1	-9	**15**	**1**	**17**	**-3**	-8	-10	-5	-9	**7**	**-1**	9	-4	**8**	**0**	8	-9	20	0
Soybean	2030	**7**	**8**	**22**	**12**	12	10	**-8**	**8**	**2**	**8**	1	8	13	9	6	11	1	7	21	9
	2090	**57**	**15**	**52**	**29**	43	19	**-6**	**4**	**19**	**11**	46	27	36	15	55	33	5	10	49	18
Peanuts	2030	8	4	**23**	**9**	**15**	**4**	-3	6	1	4	4	12	**11**	**4**	10	14	**-2**	**7**	26	5
	2090	41	7	**47**	**24**	**36**	**12**	-5	1	10	5	48	37	**28**	**10**	56	43	**-1**	**10**	43	12
Sorghum	2030	**3**	**-6**	2	-5	**7**	**-4**	**-7**	**-7**	**-2**	**-6**	-7	-11	5	-5	-3	-7	-7	-5	3	-5
	2090	**10**	**-11**	3	-7	**6**	**-11**	**-15**	**-17**	**-7**	**-13**	3	-9	5	-11	4	-7	-12	-12	-3	-13
Wheat	2030	**2**	**3**	**8**	**3**	**5**	**3**	-1	0	2	3	**7**	**3**	5	3	5	4	5	3	10	4
	2090	**16**	**15**	**21**	**14**	**14**	**11**	6	7	13	13	**20**	**15**	16	14	19	17	13	11	22	14
Rice	2030		**-1**		11		3		**0**		**2**		9		3		6		2		5
	2090		**8**		31		10		**3**		**6**		39		8		29		6		17

1- 2030 period refers to years 2021-2040 and period 2090 refers to years 2080-2099
2- The results for the top-four producing states according to the 1991-95 census are shown in bold face

These results indicate that dryland yields of peanuts will decrease in the lower Delta and along the Gulf Coast by up to 30%, but adding irrigation in those areas should increase yields by more than 30%. With these changes occurring slowly over next 25-45 years, farmers are expected to slowly increase irrigation and the marginal value of irrigation water for peanut production will increase. In addition to this trend, the water use efficiency of irrigation will decline, so even with no change in irrigated acreage, irrigation water demand will increase. Adding these two trends together indicates a strong increase in the demand for irrigation water.

By 2030 average dryland yields are expected to increase 11%, 15%, and 23%, respectively in Alabama, Georgia, and North Carolina, but decrease by 2% in Florida. These are currently the top-four producers of high yielding runner peanuts (Table 5.2). Yields changes in these states in the 2090s are projected to be double those of the 2030s.

Wheat – Winter-wheat yields are expected to increase in the southeast, except in the lower Delta and parts of Arkansas. Regional differences in predicted rainfall are the major factors controlling the response of wheat. Irrigated yields increase, following a trend similar to dryland yields (Fig. 5.3e and 5.4e). Demand for irrigation should increase by 20-50% in the Delta, where it is predicted that rainfall will decrease (Fig. 5.5e), and evaporation will increase due to higher temperatures. Table 5.1 shows dryland yield increases both in 2030s and 2090s in the top-four southeastern winter wheat growing states of Arkansas, North Carolina, Georgia and Kentucky. Irrigated yields are projected to decline relative to current levels over the same period.

Rice - Parts of Arkansas and Louisiana, where irrigated rice production is dominant, may experience 1-10% yield loss in 2030, while areas where rice is not being grown show potential yield increases (Fig. 5.4f). Increased CO_2 tends to suppress photorespiration in rice making it more water-efficient. Irrigation water use in the northern fringes of the Coastal Plain and mid-south will be reduced by 20% (Fig. 5.5f). On the other hand, demand for irrigation water will increase in the Delta and Gulf Coast areas by more than 20%, as a result of projected rainfall losses. At the level of state average yields, projected rice yields are generally unchanged in Louisiana and Arkansas by the 2030s, while elsewhere they increase by 2-11%. By 2090s, yields should increase 3-39%. The sustainability of rice production is important since much of the rice is grown in regions where there are few alternative crops. One of the major threats to rice production is increasing demand for and cost of irrigation water. For example, about

90% of the groundwater consumed in Arkansas is used for irrigation, and 70% of that is used for rice production. If the water situation does not improve in the future, farmers may have to quit growing rice and shift to other crops that require less irrigation. One alternative might be irrigated soybeans, which require less water but have not, so far, been competitive.

5.2.1.5 Agronomic Sensitivity Results

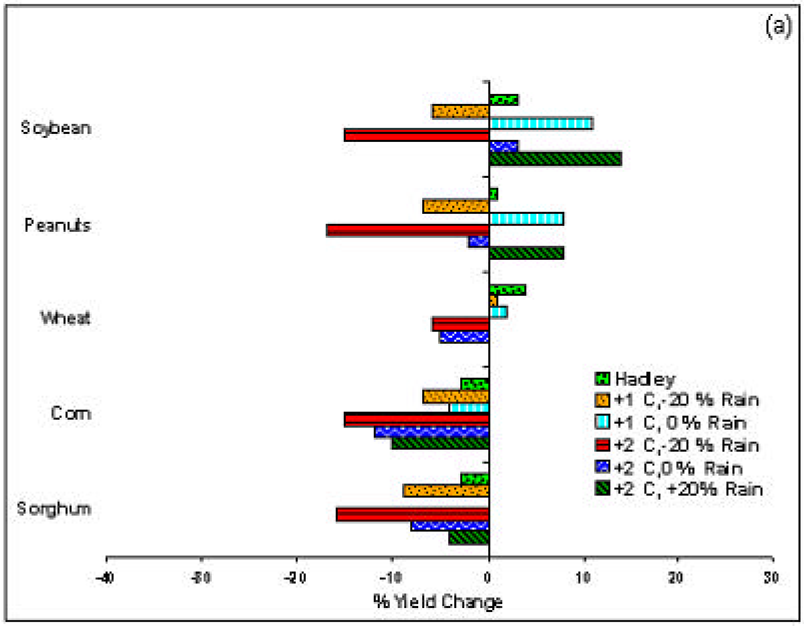
Yield changes from the Hadley climate for the 2030s and 2090s, without management adaptations, were averaged over the 10 regions for dryland and irrigated crops (Fig. 5.1). These changes were then compared with the sensitivity scenarios as shown in Figures 5.6a-5.9a as dryland or irrigated yields.

Dryland Yields- Changes in temperature, CO_2 concentration, and growing season rainfall will provide varying effects on crop yields. Under the 2030s CO_2 level (445 ppm) and current rainfall, a +1°C change in temperature should increase dryland production of soybean, peanuts and wheat, while yields of corn and sorghum would be reduced. These results suggest current temperatures are at or above optimal temperature levels for corn and sorghum, and further increase will depress yields unless new varieties become available. A +2°C increase in temperature in 2030 would cause yield losses for all crops. In contrast, the effects of 2°C temperature increase in 2090, with CO_2 (680 ppm) and no change in rainfall, should have a generally positive effect on crop yields. However decreases in rainfall by 20% accompanied by temperature increases of 1ºC to 2°C would almost double yield losses for all dryland crops studied. Simultaneously increasing rainfall by 20% and increasing temperature from 1ºC to 2 °C would offset some yield losses. Increasing CO_2 concentrations from 445 to 680 ppm would also compensate for the negative effects of temperature increases. Soybeans benefited most (22%) and sorghum least (8%).

Holding other factors constant, yields of all crops respond more to the projected increases in CO_2 levels than to the projected increases in seasonal rainfall. The magnitude of the compensatory responses to direct CO_2 varies by crop. Comparison of Figures 5.6a and 5.7a (2^oC increase, with 20% more rain and elevated CO_2), shows that peanuts, corn, sorghum and winter wheat respond more to the increases in CO_2 than to increases in rainfall, while soybeans respond about equally to both. For all crops and combinations of temperature and CO_2 changes, projected decreases in precipitation result in varying decreases in yields. Changes in yields with 20% lower rainfall were of similar in magnitude at all other temperatures and CO_2 levels simulated. This further demonstrates that soybeans are more sensitive to drought than the other crops regardless of temperature and CO_2 changes. Furthermore, results show that crop yields are much less sensitive to changes in temperature than to changes in precipitation. An increase in growing season rainfall of about 20% almost completely offset the negative effect of temperature increase. These results suggest that growing conditions in the Southeast should become relatively more favorable for soybeans, followed by peanuts, corn, sorghum and wheat, in terms of both temperature and water availability.

Irrigated Yields- Irrigated yields were simulated assuming current rainfall and varying only the temperatures from +1ºC to +5 °C. If future rainfall is higher, then irrigation requirements will decrease and if it is lower, needed irrigation will increase. Most irrigated crops were sensitive to the simulated changes in climate and CO_2

Figure 5-6. Dryland Yields in 2030s (a) Without Adaptation (b) With Adaptation



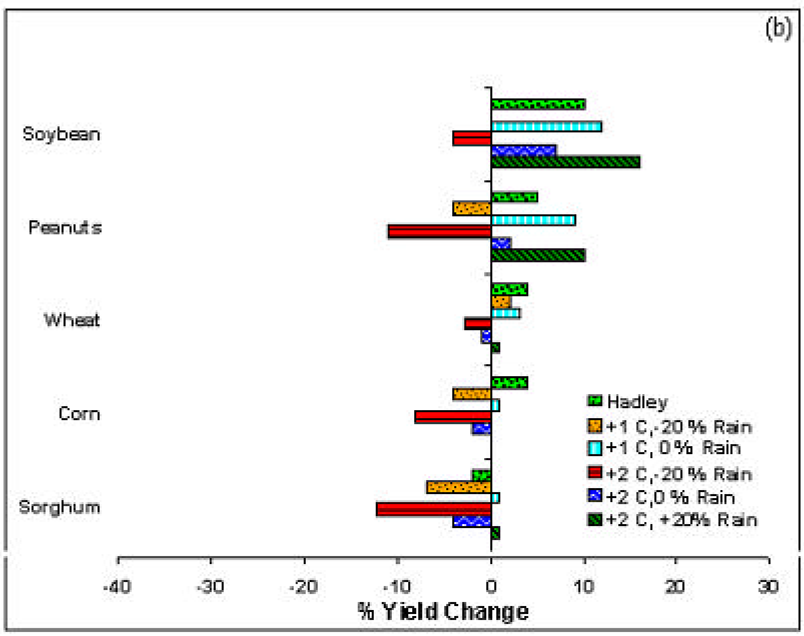
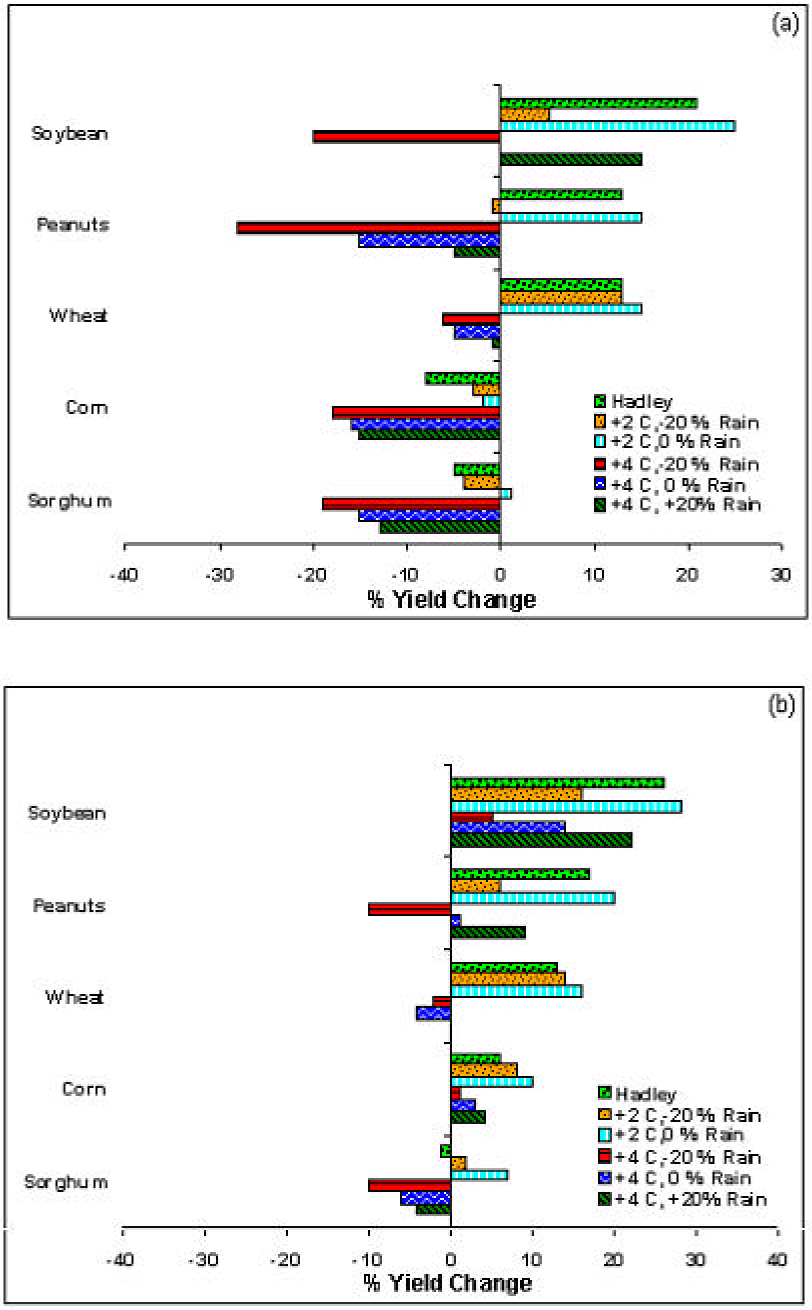


Figure 5-7. Dryland Yields in 2090s (a) Without Adaptation (b) With Adaptation



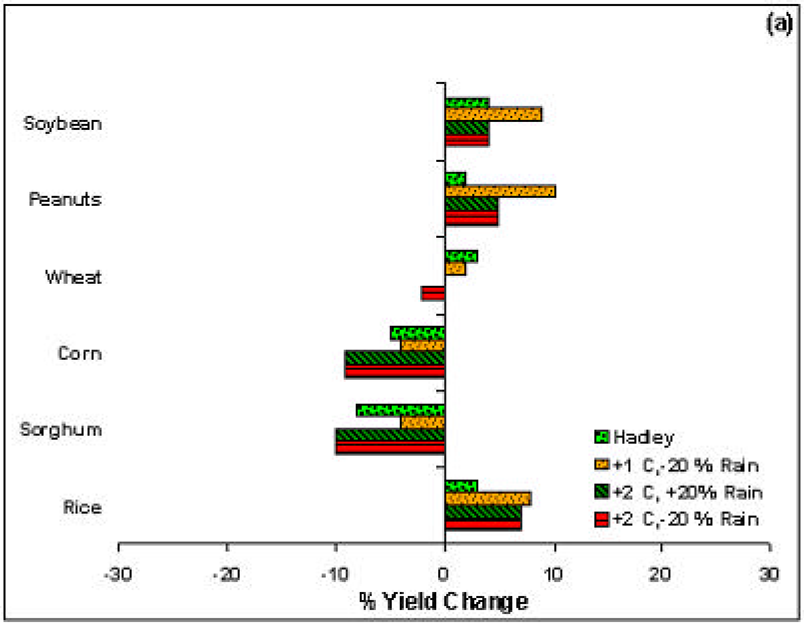
fertilization. Irrigated yields of soybean, peanuts, wheat and rice increased from current levels by 2-13% with +1 °C in 2030s and by a lesser extent, 1-9%, with +2 °C temperature rise (Fig. 5.8a). Irrigated corn and sorghum yields were predicted to decrease from the current levels. These yield losses are projected to be even greater as temperatures increase, irrespective of CO_2 fertilization. Elevated CO_2 concentration (680 ppm) will significantly enhance yields in C-3 species, and to a much lesser degree in C-4 species (Figs. 5.8a and 5.9a).

5.2.1.6 Adaptation Strategies

The sensitivity analysis above was used to identify those climate conditions that would be particularly damaging to the dryland production of soybean, peanuts, corn, sorghum and wheat in the Southeast (Table 5.3). This allowed us to consider to what extent the yields can be maintained with current management practices. As discussed earlier, future climate change may impact agriculture in the Southeast strongly. Changes in temperature and rainfall may require adaptation in management strategies. We hypothesized that changes in planting dates and maturity groups would increase yield under the climate change conditions studied.

Results of the variety-planting date adaptations study for dryland and irrigated production are shown in Figs. 5.6b –5.9b. All crops benefited from variety and planting date changes, in many cases shifting from a decreased yield without management changes to an increased yield with changes. Most dryland crop adaptations failed to completely eliminate yield losses in the 20% less rainfall scenario. Tabulated results by crop and state reveal that the optimal types of adaptation and the resulting contributions

Figure 5- 8. Irrigated Yield in 2030s (a) Without Adaptation (b) With Adaptation



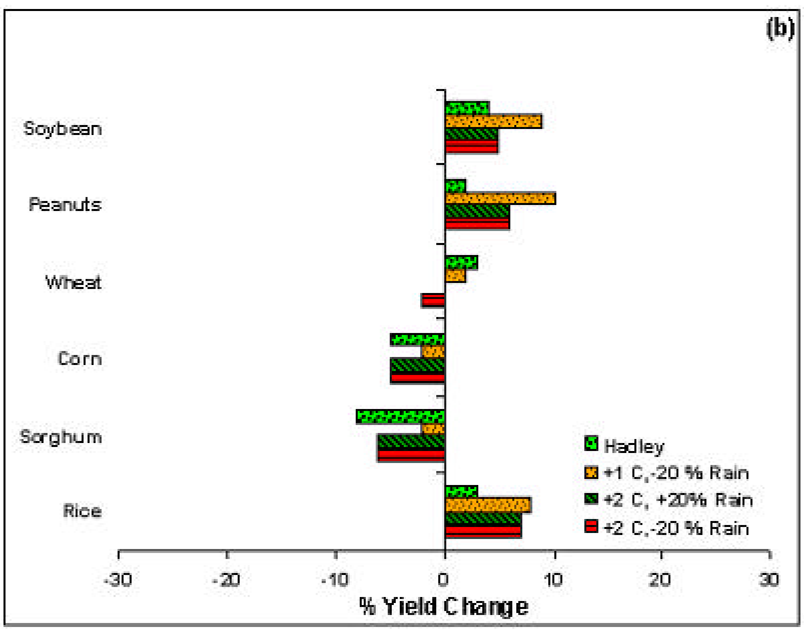
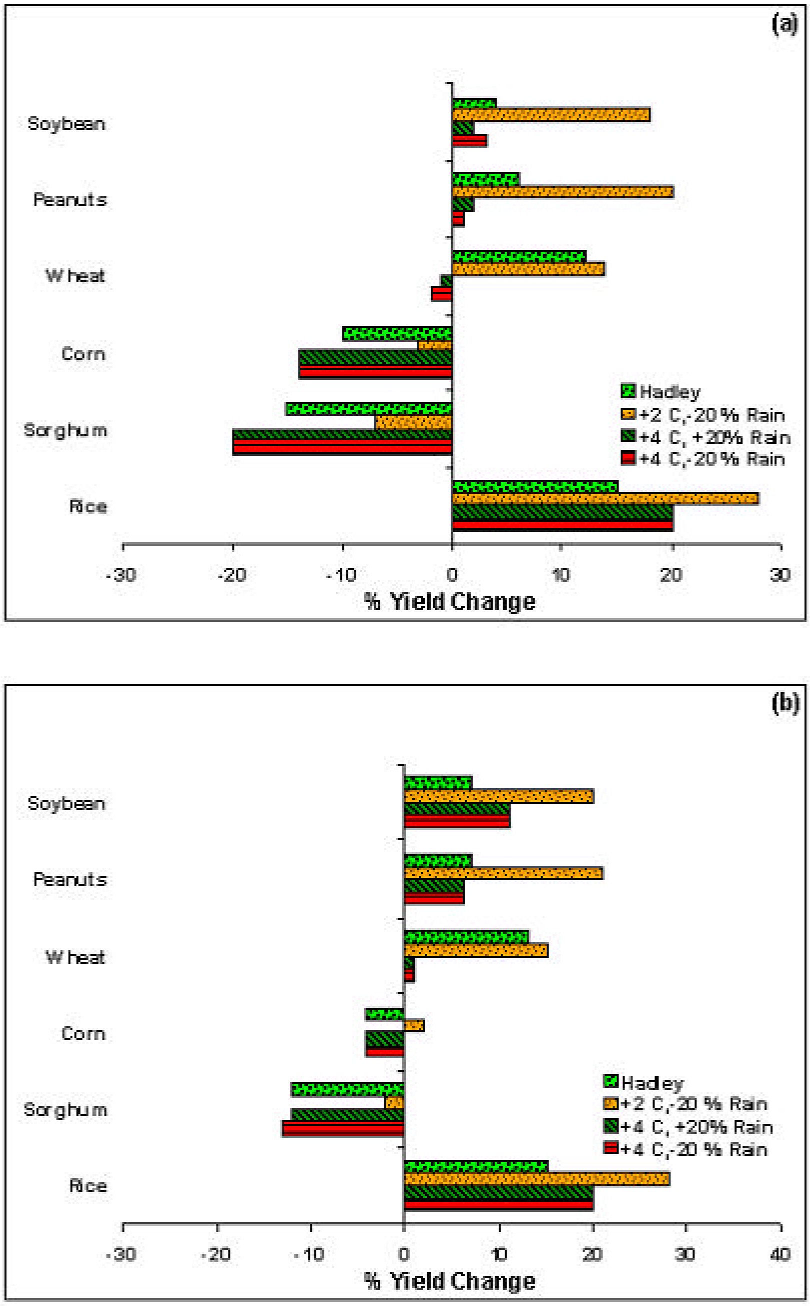


Figure 5-9. Irrigated Yields in 2090s (a) Without Adaptation (b) With Adaptation



to yield vary both by state and crop. For corn, peanuts, sorghum and wheat there may be little need to change from currently adapted varieties, under all projected combinations of temperature and rainfall changes. For soybeans, there appears to be little need to change from currently grown varieties in Arkansas, Kentucky, Mississippi and Tennessee for temperature increases up to +2 °C, however considerable advantages are estimated for other locations when selecting later maturity group varieties. For soybeans, peanuts, and sorghum as the rainfall decreases and temperatures increase, delayed planting appears to be the best option. Corn, however, may perform better if planted earlier. These benefits from the earlier planting of corn apparently stem from cooler conditions during the reproductive period of growth and possibly from more favorable water availability during this critical growth phase. Later planting dates also entail the need for later maturity group (MG) varieties.

Table 5.3 Temperature tolerance limits for crops to projected rainfall changes in 2030s and 2090s*

	445 ppmv CO_2 as in 2030s			680 ppmv CO_2 as in 2030s		
	Change in Current Rainfall			Change in Current Rainfall		
	-20%	0%	20%	-20%	0%	20%
	Temperature Tolerance					
Soybean	+0	+1	+3	+1	+3	+4
Peanuts	+0	+2	+3	+2	+3	+4
Corn	+0	+0	+1	+2	+3	+3
Sorghum	+0	+0	+1	+1	+1	+1
Wheat	+0	+1	+2	+3	+3	+3

* The numbers indicate that, yield will decrease compared to the current values if temperature exceeds the current value more than the value indicated for a particular change in rainfall amount.

5.2.2 Agricultural Economics

Projected climate-induced impacts on the economics of agricultural production vary greatly across the Southeast. A linked simulation models approach was employed to derive insights into how the economics of the agricultural sector might be influenced by the projected climate changes. Selected field level results from the agronomic simulations of the Hadley model base, 2030 and 2090 scenarios were combined with county level geo-physical and agricultural enterprise data to derive applicable farm level changes.

Since cotton is an important field crop in many areas of the Southeast, the agronomic results reported above were expanded to include cotton with the six grain crops studied. Cotton responses to the climate change scenarios were estimated by keying them to soybean responses, an agronomically similar crop. The crop response data were, in turn, used in a farm management economic simulation model to estimate how a typical farmer from a selected, agriculturally important and diversified location in each of the 10 southeastern states would likely respond to the projected climate changes. The changes estimated include changes in crop mix, water use and farm incomes (Davidson et al., 1995). These typical farm results were then scaled on a weighted average basis to obtain regional and state level estimates of overall changes in agricultural production and water use. It is important to note that this weighting eliminates areas not engaged in real production, a much different premise than that of the previous agronomic simulations. The estimated farm income changes were also provided to the land use phase of this study to provide inferences on how land use change, particularly between the forest and agricultural sectors, might be influenced by climate change (see land use discussion below).

5.2.2.1 Economic Simulation Methods

The simulation results obtained in this study are inevitably influenced by modeling assumptions imposed to facilitate region-wide comparisons. In some cases, these assumptions may have implications that distort results, particularly for atypical areas within selected areas. Put another way, assumptions judged appropriate in order to standardize results and isolate the impact of climate, may result in unexpected effects in specific locales with any of the following characteristics:

(1) only a small number of crops are profitable (the economic optimization only considers profitable alternatives);

(2) the use of irrigation is very low (thereby greatly decreasing the alternatives available for consideration);

(3) projected benefits from double cropping (winter wheat) are overstated in the optimization model.

(4) a combination of harvesting constraints and few profitable crops unduly constrain management adaptations.

5.2.2.2 Results

Indices are used in presenting these results in order to illuminate the relative impacts, as opposed to absolute estimates. This conveys general impact estimates without a false sense of numerical precision. Projections of relative changes are fundamental in economic analyses and succinctly encapsulate information on future trends. Two types of indices are used: temporal and competing alternatives. The former focuses on relative changes from baseline or current conditions whereas the latter suggests relative impacts among competing alternatives. Results were estimated for the following: yield changes (from crop baselines), relative yield changes (among study crops), changes in crop mix (from baseline), relative changes in crop mix (among Forest Inventory Assessment (FIA) districts), changes in water use (from baseline), relative water use changes (among study crops and FIA districts), farm income (from baseline), and relative farm income (among FIA districts). A set of maps depicting these indices for corn, water use, and farm income is presented in figures 5.10 through 5.19. [A full set of maps for all crops has been developed, and can made available upon request.] Relative impacts are particularly useful in evaluating the influence of projected climate changes on the competitiveness of agricultural enterprises. The yield data used were derived from USDA county averages proportionately modified by data from the previously described agronomic simulations. The indices reflect only districts judged agriculturally important, using a criterion of at least 50,000 acres planted to any of the seven study crops, based on the 5-year average (1994-1998) reported in the USDA's Census of Agriculture. The yield maps project the data on a county basis, and depict Hadley Scenario yield changes weighted by current production, so that yield estimates for counties with little or no production do not show up. Water use and farm income maps project the data on the basis of FIA reporting districts. This projection was used to facilitate data coordination with the land use planning group studies reported in a subsequent section of this document.

Estimated changes in crop mix and the resulting changes in water use and farm income were developed using a linear programming (LP) farm management optimization model. The indices for relative yield impacts were calculated using the county result divided by a weighted regional average. Similarly, the percent change in yield for the selected crop in a given county was divided by the regional percent change for that crop and year, as weighted by the share of that crop in the regional total. County share was calculated as the 5-year average from 1994-1998. As before, all counties were included in the calculation of the weighted regional average, but only those counties that averaged at least 5,000 acres of the given crop are depicted in regional maps, to focus attention on results from important agricultural areas.

5.2.2.2.1 Summary Results by Crop

Corn. Results for dryland corn in 2030 and 2090 are presented in Figures 5.10 and 5.11. The regional weighted average yield change for dryland corn was 3.95% in 2030 and 3.57% in 2090. In 2030, the Coastal plain derives the largest benefits, and the Tennessee Valley region also indicates positive impacts. The Delta and Gulf Coast regions are the most negatively impacted, and the pattern of negative impacts indicated in the Delta extends into the Ohio River and central areas of Kentucky. In 2090, the negative impacts become more pronounced in the Delta and Gulf Coast regions. Central Kentucky experiences a somewhat improved relative condition and the positive impacts shown in 2030 decline somewhat in the Coastal Plain of North Carolina.

The results for irrigated corn differ from dryland largely because of a lack of temperature mitigation from increased precipitation, since irrigation is relied upon to

Figure 5- 10. Climate-Induced Yield Changes: Dryland Corn in the Southeast U.S. 2030 (Hadley Scenario)

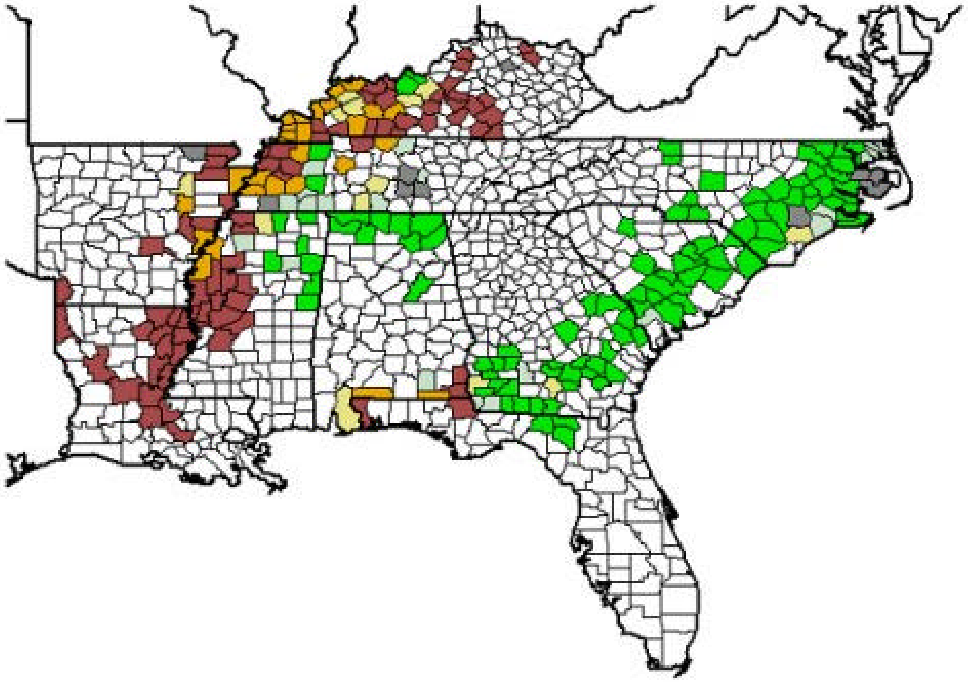
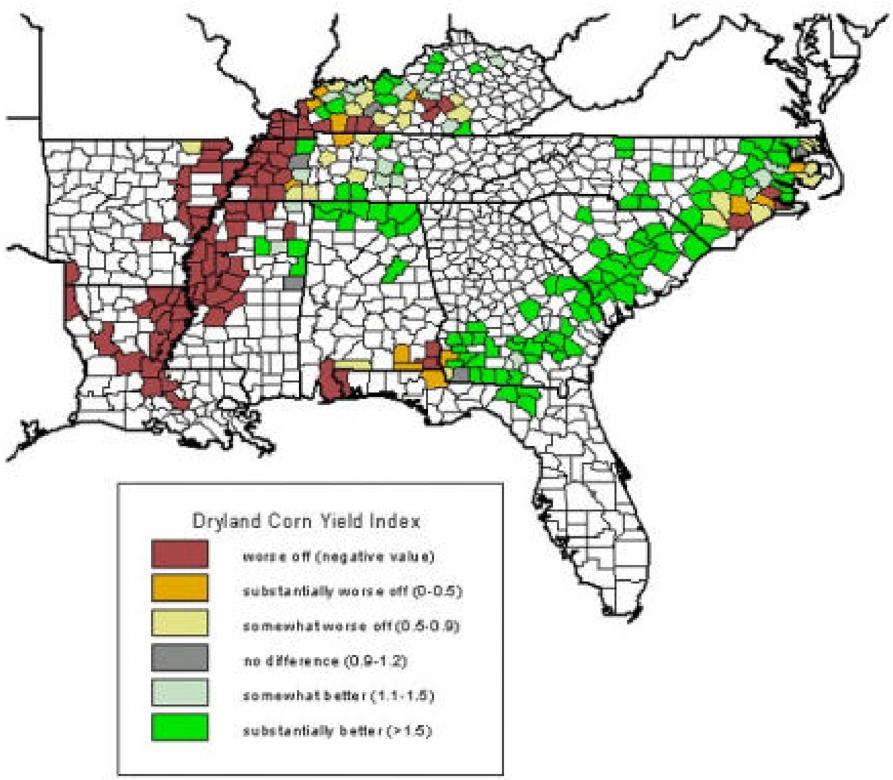


Figure 5- 11. Climate-Induced Yield Changes: Dryland Corn in the Southeast U.S. 2090 (Hadley Scenario)



supply the water requirements. Dryland results are based on increased precipitation in most places concurrent with warming; however, irrigated crop scenarios do not include this offsetting benefit of additional precipitation, in order to isolate water usage changes. Yields for irrigated corn are thus negative region-wide by 3.84% in 2030 and 1.38% in 2090 (Figs. 5.12 and 5.13). These irrigated results will serve to isolate the effects of higher temperature and higher CO_2. In relative terms, irrigated corn producers in the Coastal Plain of North and South Carolina and the Tennessee Valley growing areas experience an improvement in their competitive position; however, the incentive to irrigate corn is diminished by the combined effects of increased yields on dryland and reduced yields on irrigated. Areas most negatively impacted include the Mississippi Delta and Gulf Coast areas extending north into southeastern Alabama and southwestern Georgia. The same trends are repeated in 2090, except that relative yield benefits accrue to western Tennessee and the Tennessee Valley.

Soybeans. Yield changes for dryland soybeans are generally positive throughout the region with a weighted average yield increase of 7.96 % in 2030 and 18.07% in 2090. Areas of negative yield impacts, on an absolute basis, are most of Louisiana, the lower Mississippi Delta, the Gulf Coast in Alabama and Florida, and central Kentucky. Positive impacts are concentrated in the Coastal Plain from Georgia to North Carolina. In 2090, the benefits of climate effects are reduced in much of the Coastal Plain and relative improvements shift more into the Tennessee Valley, western Tennessee and Kentucky.

Figure 5- 12. Climate-Induced Yield Changes: Irrigated Corn in the Southeast U.S. 2030 (Hadley Scenario)

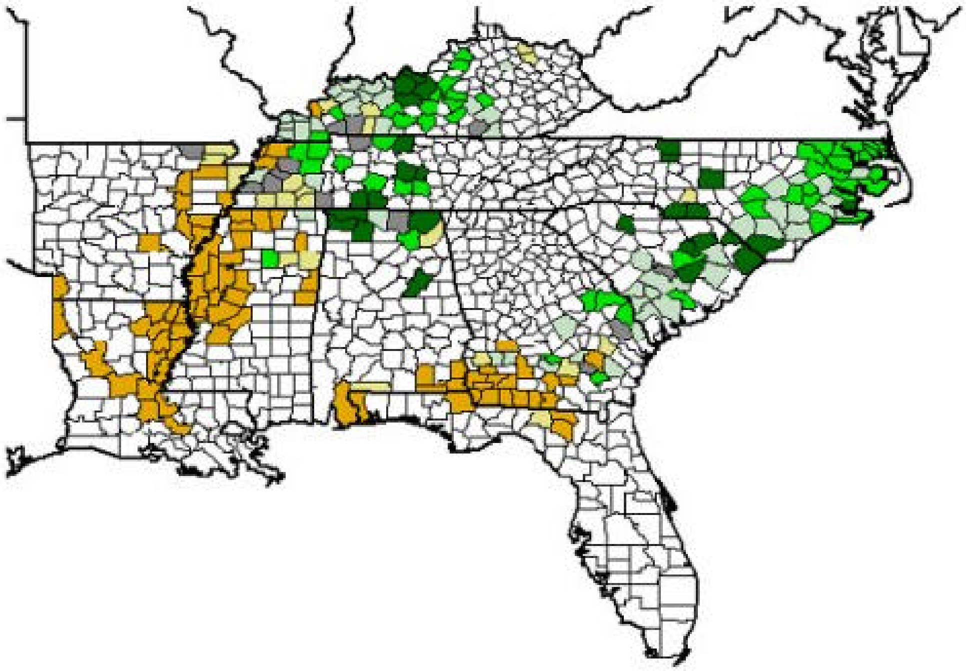
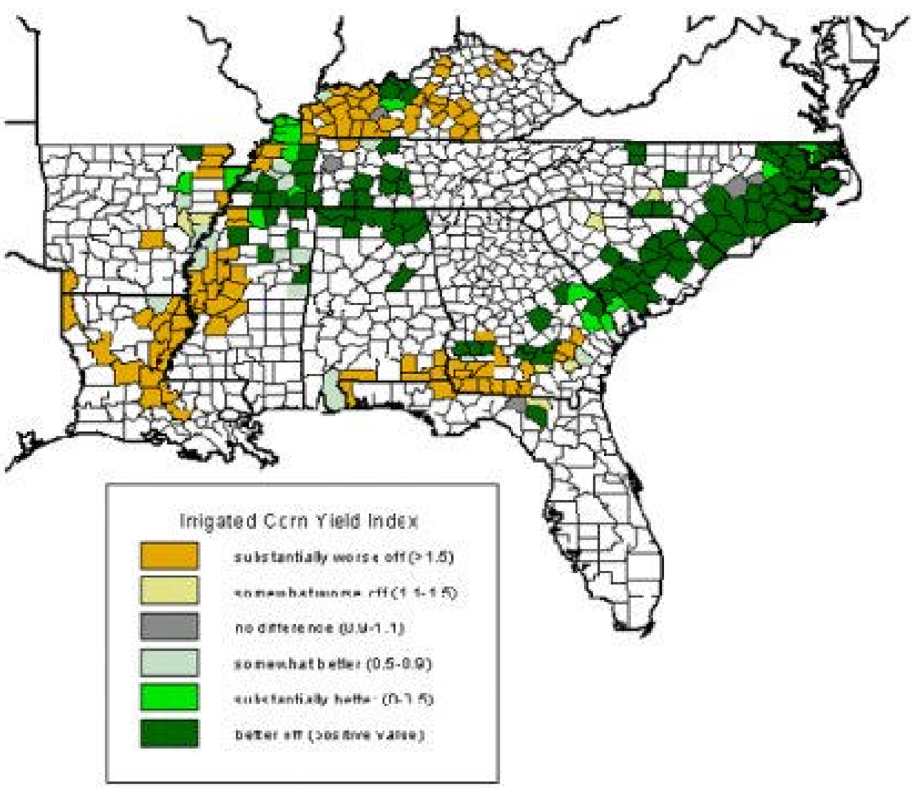


Figure 5- 13. Climate-Induced Yield Changes: Irrigated Corn in the Southeast U.S. 2090 (Hadley Scenario)



Irrigated soybean production is most common in the Delta region; thus the projected negative results in the Delta are magnified, since this is the area where irrigated production is prevalent. The regional average impact is 7.39% in 2030 and is 15.26% in 2090. The Tennessee Valley region is the most positively impacted area in 2030. In 2090, the results shift, as the Louisiana portion of the Delta and the Gulf Coast areas of Alabama and Florida are adversely affected and the benefits become concentrated in the northern Delta and northern Coastal Plain. Results projected for 2090 evidence a strong north south division, generally resulting from the impact of greater heat stress in the southernmost areas.

Wheat. In 2030, a relative advantage for the northern portions of the Coastal Plain is evident. Starting in south central Georgia and moving north through the agricultural counties of South Carolina and North Carolina, the Hadley scenario evidences a distinct advantage to increasing the practice of double cropping with winter wheat. This same advantage is not the case moving south, starting in southwest Georgia and continuing into Alabama and Florida. Several counties experience absolute negative impacts, not just relative losses. The Delta region is relatively worse off, while only a few dispersed counties in Alabama, Tennessee, and Kentucky show substantial improvements.

The 2090 impacts on winter wheat are less obvious. No counties experience negative impacts on an absolute basis and there are few counties that are either substantially better or worse off on a relative basis. The slight warming in 2030 is actually helpful to winter wheat; however, the more intense warming simulated for 2090 is not. The agronomic causes of these simulated changes were discussed in the previous section on changes in agricultural yields.

Sorghum. Current sorghum production is concentrated in the Delta region, with substantial acreages in only a few counties in other areas of the Southeast, based on the stipulated criteria for inclusion in the index of at least 5,000 acres.   Dryland sorghum production in the Tennessee Valley of Alabama and in southwest Georgia benefits in both 2030 and 2090. Benefits in the Delta region are largely concentrated in Arkansas with Louisiana enduring the greatest negative impacts, both in its dryland and irrigated production. In fact, no county in Louisiana in either time period shows any beneficial impacts to either irrigated or dry production.

Peanuts. Peanut acreage has been geographically limited by government commodity programs that attached eligibility for government marketing quotas to farms or individuals with established production histories. These programs are being phased out, but the exact nature of future agricultural policy is not yet clear. Also, because of the high value of the peanut crops under past commodity support programs, many peanut farmers have invested in irrigation systems.

In 2030, the northern peanut growing areas are found to be substantially better off and many counties in the southern growing area worse off both relatively and absolutely. The same picture emerges for 2090. From these results it would appear that peanut production is likely to move out of Florida altogether if climate changes evolve according to the Hadley projections.

Irrigated peanut production is relatively less impacted by climate change than dryland, as expected. In fact, the same areas in Florida that show negative impacts for dryland peanuts show improved conditions for irrigated peanuts in 2030. In 2090, yield benefits to irrigated production are concentrated in North Carolina. Peanut production in both time periods and for both irrigated and non-irrigated production are projected to be impacted negatively in the peanut growing areas of Georgia, which is currently the leading peanut production area in the U.S.

Rice. Most of the commercially grown rice in the Southeastern US is irrigated and currently located in the Mississippi basin. As discussed with peanuts, this pattern of crop planting is tied to government commodity programs that are being phased out, but existed during the period of the data used for this study. Future policy is not certain. It should be noted that crop mix changes involving rice entail substantial fixed costs, particularly land preparation, relative to most other row crops. In general terms, rice production is benefited in the southern and central Delta in 2030 and in the north Delta in 2090. The estimated impacts in 2090 are less dramatic than those in 2030

5.2.2.2.2 Crop Mixes

Corn. In 2030, dryland corn increases in importance in southeastern crop mixes (Figs 5.14 and 5.15). In central North Carolina and southeast Georgia, strong incentives will emerge to add corn to crop mixes in areas where it is currently not economical. In northwest Arkansas, a substantial increase should occur and in southwest Alabama a moderate increase is projected. Other areas are relatively less affected.

Figure 5- 14. Climate-Induced Crop Mix Changes: Dryland Corn in the Southeast U.S. 2030 (Hadley Scenario)

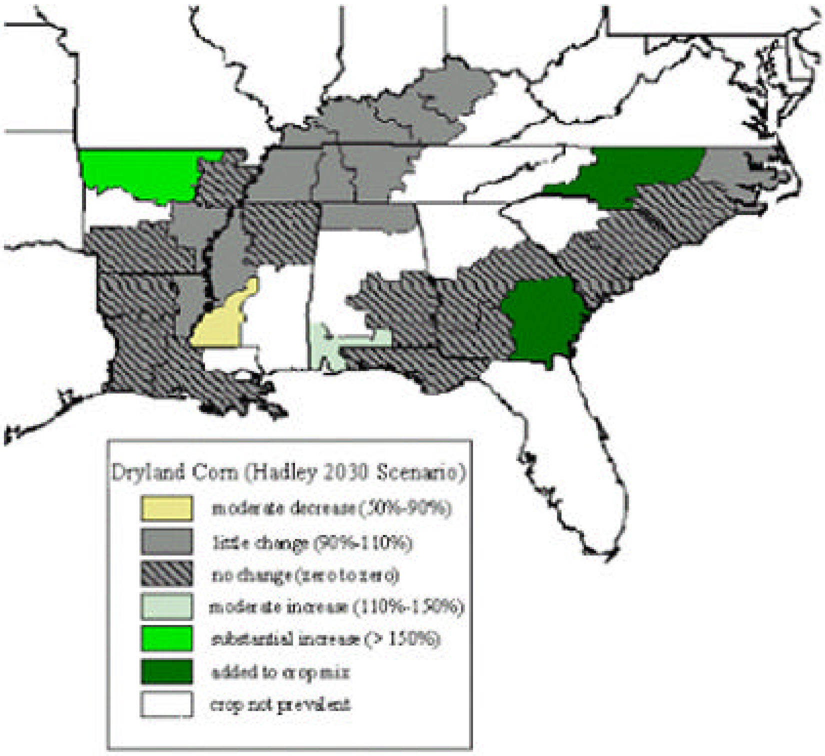
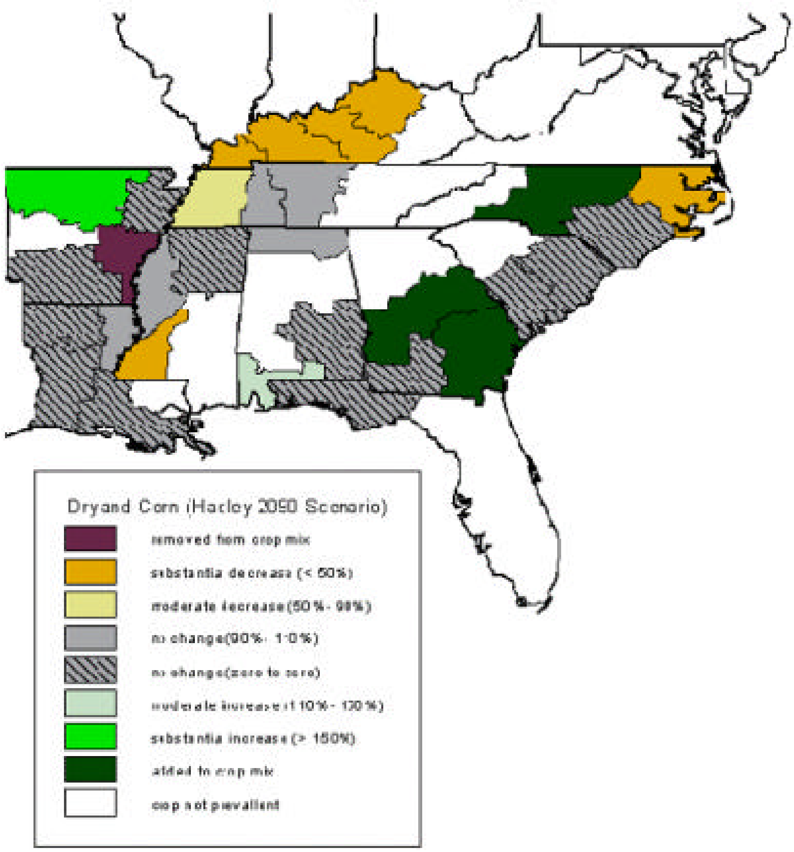


Figure 5- 15. Climate-Induced Crop Mix Changes: Dryland Corn in the Southeast U.S. 2090 (Hadley Scenario)



Southern Arkansas is the only area within the region where corn is projected to disappear from crop mixes. Throughout most of the Coastal Plain, irrigated corn is projected to decline in importance. A similar decline is also evident in a couple areas of the Mississippi Delta.

In 2090, results are much more heterogeneous. That is, for both dryland corn and irrigated corn, rather substantial positive and negative changes are expected in corn's share of projected crop mixes. For dryland corn, most of the increases in importance occur in the Coastal Plain and most decreases are in the Mississippi Delta. Dryland corn shows a particularly positive effect in Georgia and particularly negative effect in western Kentucky. The pattern with irrigated corn is almost exactly the opposite. The implication of these two results is a shift for corn from irrigated to dryland production in the Coastal Plain, and possibly a smaller shift into irrigated production in the Delta.

Cotton. In 2030, dryland cotton decreases in the Coastal Plain of North and South Carolina and Georgia. Gains in dryland cotton are suggested for southeastern Georgia and southeastern Alabama. Irrigated cotton is unchanged in most of the Coastal Plain, except for a moderate reduction in Georgia and moderate increase in southeast North Carolina. A stimulus to increase irrigated acreage is seen in several sections of the southern Delta.

In 2090, dryland cotton becomes more important in southeast Georgia, central Georgia and southeast Alabama. The coastal plain of North and South Carolina will experience a decrease in dryland cotton's share of crop mixes. In the Delta, dryland production becomes more important in several areas, while it diminishes in southeast Louisiana. Irrigated cotton in 2090 is either unchanged or negatively affected, except for one district each in southwest Arkansas and southwest Mississippi.

Peanut. Current peanut production is limited to the Coastal Plain, primarily because of US government commodity programs. In 2030, dryland peanuts appear to be disadvantaged by the simulated climate conditions in all areas except southwest Georgia. Substantial decreases are suggested for dryland peanut production in South Carolina. Irrigated peanuts show a decline in Georgia and an increase in the panhandle of Florida. In 2090, the irrigated result from 2030 is replicated except that the decline in irrigated peanuts becomes more pronounced in southwest Georgia. Dryland production continues the pattern of 2030, with the additional result that dryland peanuts may become substantially more important in eastern North Carolina than they are at present.

Rice. Virtually no rice is produced on dryland, and current southeastern rice production is found only in the Mississippi basin. In no area does rice become less important, and in southwest Arkansas it increases in importance in 2030. In 2090, rice is projected to enter into the crop mixes of eastern Louisiana and western Arkansas.

Sorghum. Sorghum has generally been a minor crop in the Southeast. Southeast Alabama may show a further decrease in both 2030 and 2090 with northwest Arkansas also showing a decline. The only increase in sorghum’s share of crop mixes occurs in southeast Arkansas. Because sorghum has often been used as a relatively drought-resistant crop, the additional precipitation associated with the Hadley scenario diminishes its importance.

Soybean. Soybeans are a crop that exhibit a variety of responses in both 2030 and 2090 throughout the Southeast, both for dry and for irrigated production. Dryland and irrigated soybeans decrease in importance in Coastal Plain crop mixes of 2030 and 2090, except for irrigated production in southeast Georgia. Increases in irrigated soybean's share of 2030 crop mixes in southwest Georgia are substantial, but are only moderate in 2090. In the Delta, the climate effects are more heterogeneous than in the Coastal Plain. Dryland soybeans are generally adversely affected in Louisiana, while irrigated soybeans are benefited. A shift from dryland to irrigated soybeans is projected for Louisiana. Irrigated soybeans are not very prevalent on the eastern side of the Delta and the projected climate scenarios do not change this outlook. Irrigated soybean's crop shares are generally positive on the western side of the Delta, except for east central Arkansas.

Wheat. The use of wheat as a winter crop is likely to expand, based on the climate changes as projected by the Hadley Model. This is particularly true in the Coastal Plain, where double cropping winter wheat, particularly with soybeans, could become prevalent. Wheat is generally not irrigated because ample moisture from precipitation is normally available in winter months throughout the Southeast. Projected climate changes do not suggest that the returns to irrigation of winter wheat will improve.

5.2.2.2.3 Water Use

The water use index was constructed by taking the simulated changes in water use from the agronomic simulations and weighting them with the irrigated crop acreages from the farm management LP model. Districts that did not have a minimum amount of agriculture, as described above, are therefore not included in the index, and the regional average reflects only agronomic projections from districts with substantial agricultural production.

Changes in water use (Figs. 5.16 and 5.17) in agriculture generally show a north-south division to increases or decreases in water use. In 2030, the simulated results show the Southeast with an average decline of 13% in water use for crop irrigation. Within the Southeast, North Carolina, the northern Mississippi Delta, the Tennessee and Ohio River areas exhibit the largest reductions in irrigation. It should be noted that these areas tend to be the least irrigated areas in the Southeast, so the estimated percent changes stem from a rather low baseline. Results also indicate a clear stimulus for increasing irrigation in the southern portions of the southeast, particularly in Louisiana, lower sections of the Delta and the Gulf Coast and lower portions of the Coastal Plain where irrigation is widespread. Increases in irrigated acreage might also emerge in south Georgia, south Alabama and the Panhandle of Florida.

The 2030 results become more dramatic with the projected changes for the 2090s. That is, the relative impacts are more dramatic with decreased demand for irrigation

Figure 5- 16. Climate-Induced Water Use Changes: Total Water Use for Crops in the Southeast 2030 (Hadley Scenario)

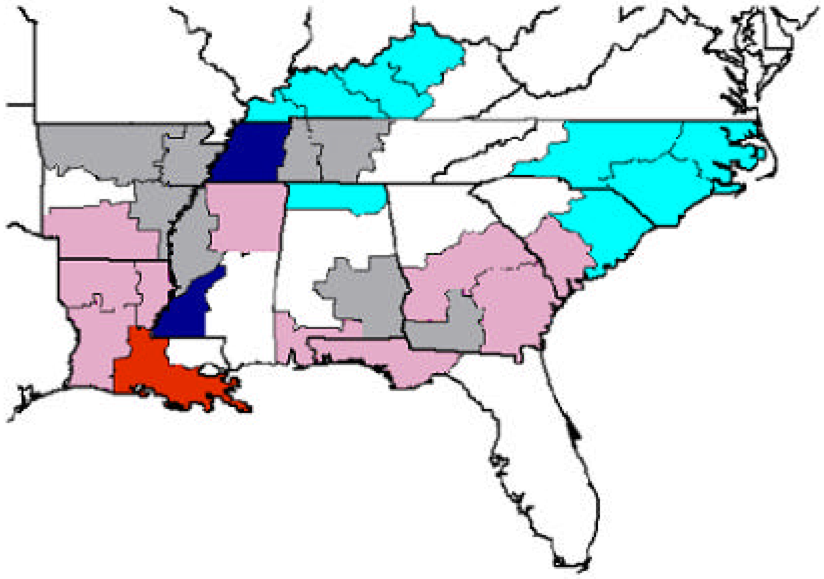
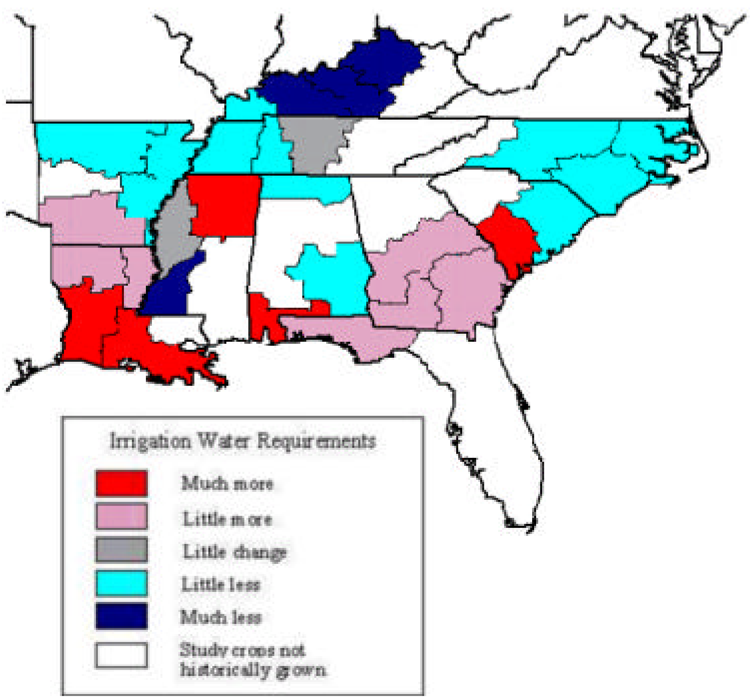


Figure 5- 17. Climate-Induced Water Use Changes: Total Water Use for Crops in the Southeast 2090 (Hadley Scenario)



water in the northern tier of the region and relatively greater demand for irrigation water in the southern tier. In 2090, the overall average is a reduction in water demand of 37%. Southern Louisiana, southern Alabama, the panhandle of Florida and South Georgia are expected to have the largest relative increases in demand for irrigation water.

5.2.2.2.4 Farm Income

Changes in net returns above variable costs of production, as simulated in the agricultural economic simulation model, are shown in Figs. 5.18 and 5.19. Recall that FIA districts that do not meet the minimum requirement of 50,000 acres current production are weighted out of the index, as previously explained. In 2030, farm incomes in the Mississippi Delta portions of Louisiana, Mississippi and Arkansas, as well as the Gulf Coast areas of Alabama, Florida and Georgia and the Ohio River in Kentucky are negatively impacted. However, the weighted average for the entire Southeast shows an income gain of 29%. The gains are concentrated in central and western Tennessee, and the Coastal Plain of Georgia, South Carolina and North Carolina. In 2090, benefits follow a pattern similar to that of 2030, only they are less consistent, with benefits being indicated for portions of Alabama and Arkansas that had previously not shown any, and losses appearing in Tennessee.

5.2.3 Summary

Several major trends can be discerned from the economic modeling. If the climate changes as suggested in the simulation scenarios, much of the row crop agriculture of southeast Alabama, north Florida and southwest Georgia could shift gradually northward

Figure 5- 18. Climate-Induced Income Changes: Total Income from Crops in the Southeast 2030 (Hadley Scenario)

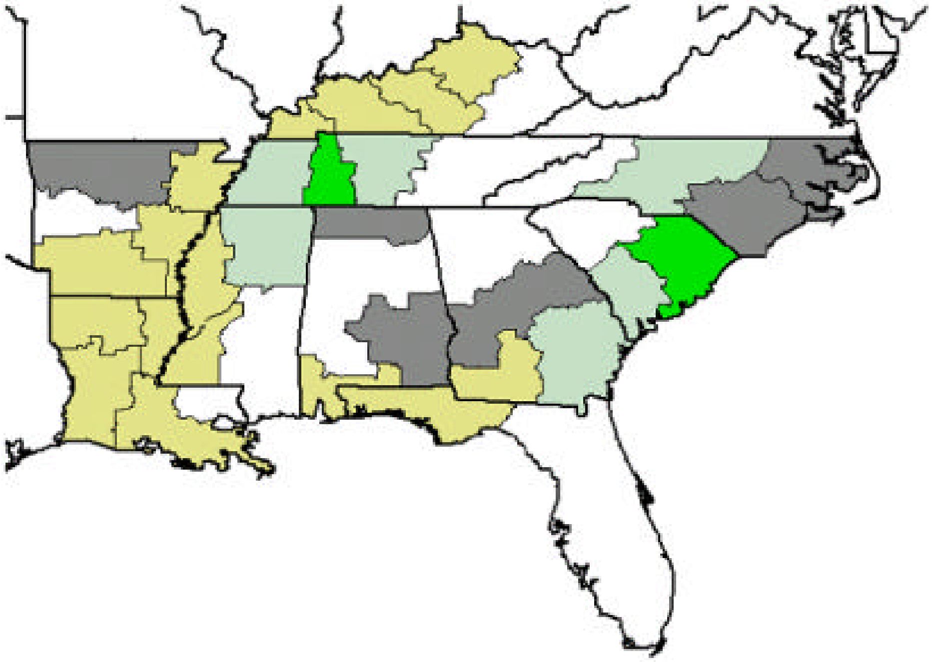
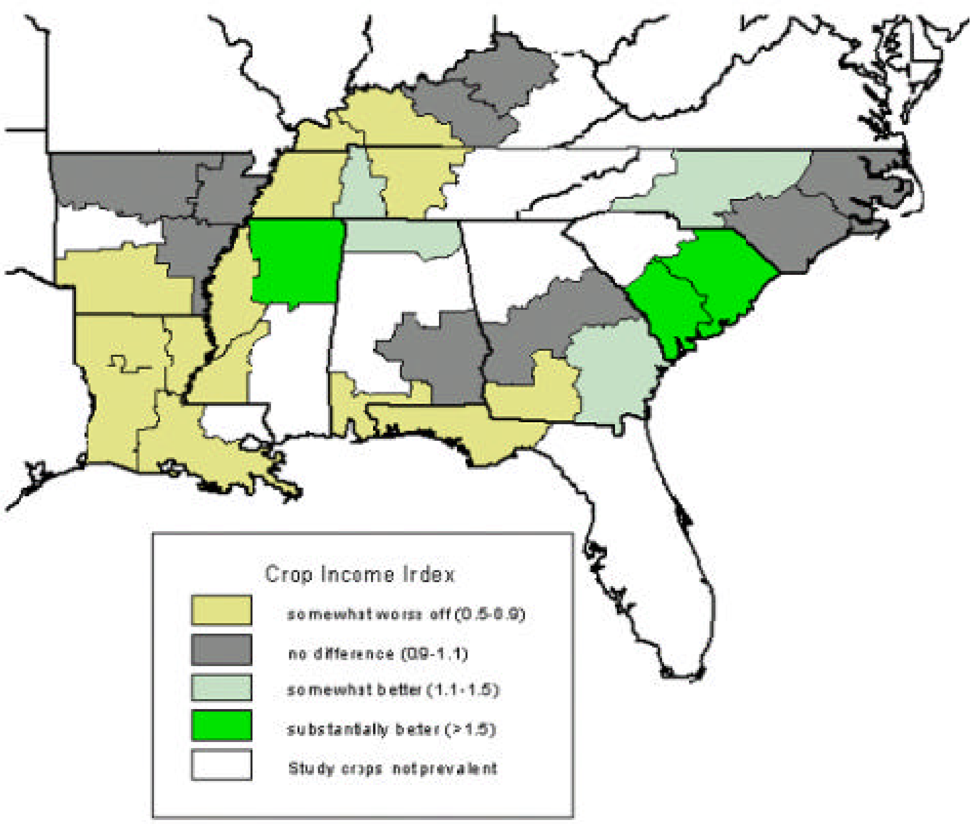


Figure 5- 19. Climate-Induced Income Changes: Total Income from Crops in the Southeast 2090 (Hadley Scenario)



into central Georgia, South Carolina and North Carolina. In addition, growing areas of the southern Delta are expected to fare relatively worse than central and northern growing areas. These results are mostly expected to accelerate existing trends, in which much of the specialty agriculture previously located in Florida has been moving northward, into Georgia and Alabama. The potential movement of row crops into South and North Carolina as suggested in this analysis is simply a further progression of this trend. The Delta growing areas of Louisiana are particularly prone to negative impacts.

These projections were formulated on the bases of existing agricultural production and markets. Probable consequences of changes in government policies and/or market conditions are not included. Nonetheless, climate-induced changes in agricultural production will inevitably occur within a larger context of emerging national and international trends, particularly those involving trade with Mexico (NAFTA) and the increasing urbanization of the Southeast.

Chapter 6

Forest Process Assessment

6.1 Historical Perspective

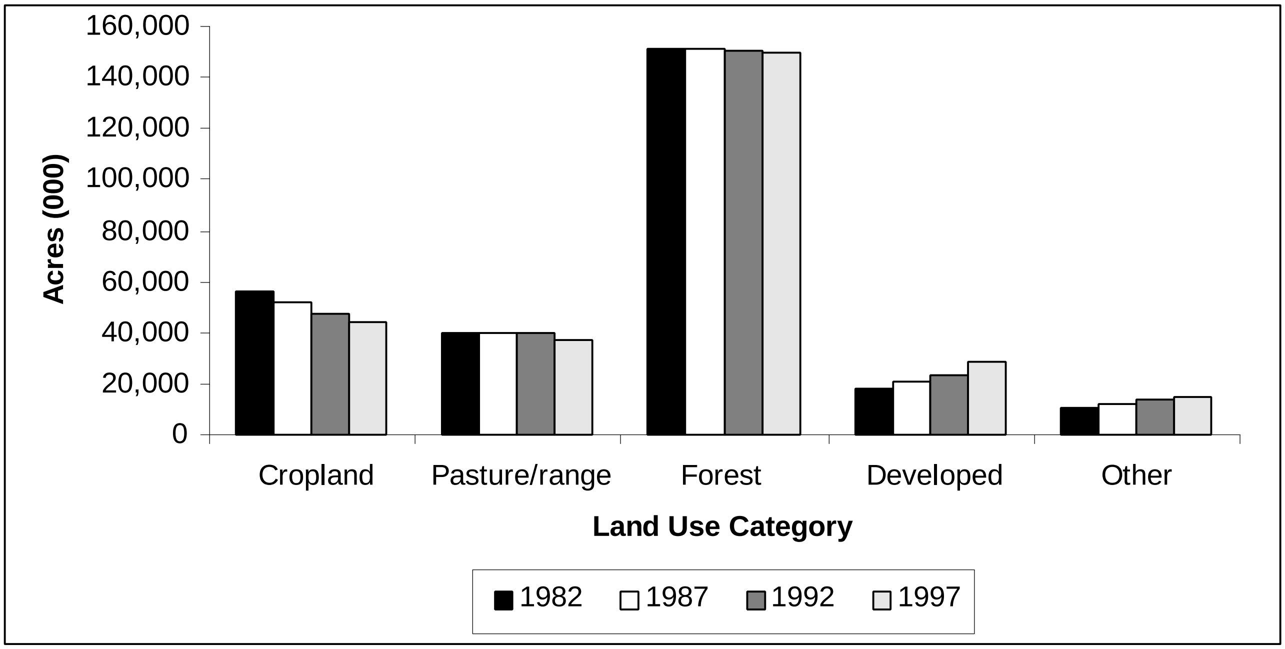
Most of the native southeastern forests had been converted to farmland by 1920, with a large percentage of this conversion prior to the Civil War. By 1860, about 43% of the total land area in the Southeast was reported as farmland, but a substantial part of the farm holdings remained in forest, which was often used as a place for grazing livestock (USFS, 1988). Southeast lumber production peaked in 1909; with continued expansion of settlement, timberland continued to decline until the early 1920s. Significant changes in agriculture took place after 1920 that caused abandonment of large areas of crop and pasture land. These included the boll weevil, which made cotton growing unprofitable in many parts of the Southeast. Some of this abandoned land was planted with trees, but the majority reverted naturally to forest leading to increases in timberland acreage (USFS, 1988).

By the late 1950s and early 1960s, the decline in timberland began again in the Southeast, caused primarily by the clearing of forest for soybeans and other crop production. Much of this timberland reduction occurred in the bottomland hardwood forest areas of the Mississippi Delta. Forest reductions were further fueled by growth in urban areas, highways and power lines, and related development. Throughout the 1970s, timberland was cleared for agricultural use and for an expanding export market.

The Natural Resources Inventory (NRI) has intensively surveyed the nation's land use since 1982. NRI data (Natural Resource Conservation Service, 1999) are used to construct land use trends on non-federal land in the Southeast by the major categories from 1982 through the most recent survey year 1997 (Fig. 6.1). Forest covers almost three-fifths of the region's land area and agriculture (cropland and pasture combined) accounts for almost one-quarter. The remainder of the land includes all urban-developed uses (about 10%) land as well as rural lands not categorized above (e.g., farm structures, marshlands). Lands under the Conservation Reserve Program (CRP) are included under "other". From 1982-1997 the region experienced a rather substantial decline in agricultural land and a dramatic increase in developed land. Cropland losses amounted to 11.6 million acres (21%), pasture/range declined by 3.3 million acres (8%). Meanwhile, urban-developed land area rose by 10.6 million acres, a 57% increase from 1982 levels. Over the same period, aggregate forest area change was fairly small -- about a 1.7 million acre decline (1.1%), but this does not imply that the forest base was static. Forestland was also converted to developed uses, but movement of land from agriculture to forest nearly offset those losses. The balance of land that left the categories of cropland, pasture-range, and forest but is not accounted for in urban-developed uses is primarily in the CRP category (about 3.2 million acres). Note that much of the region's CRP land is in trees, but is nonetheless classified separately by NRI.

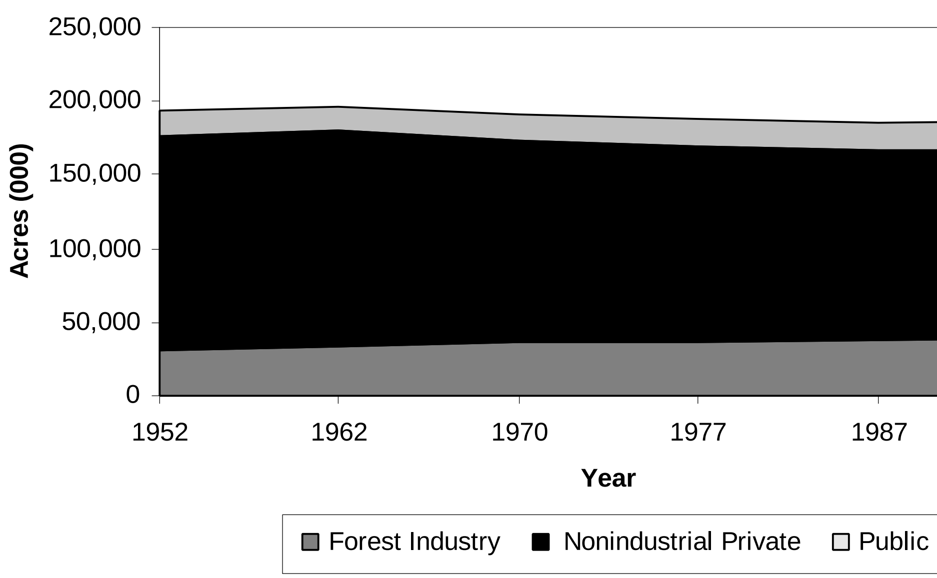
Figure 6.2 provides a look at forestland trends further back in time. Total forest area rose in the 1950s, then declined from the 1960s through the mid-1980s and stayed relatively stable through the early 1990s. The trends in forestland by ownership type indicate a couple of key points. First, the region's forest base is overwhelmingly in

Figure 6- 1. Major Uses of Non-federal Land in the 10 Southeastern States: 1982–1997[a]



[a]States included: AL, AR, FL, GA, LA, MS, NC, SC, TN, VA.
Source: NRI. 1999.

Figure 6- 2. Timberland Area Trends for the Southeast Region:1952–1992



Sources: Alig et al. 1990.
Powell et al. 1994

private hands (over 90%), predominately non-industrial private forest (NIPF). However, NIPF has declined as a share of ownership, with slight gains by forest industry and public forest lands. More detail on NIPF ownership trends is found in Moulton and Birch (1995).

6.2 Potential Impacts of Climate Change

6.2.1 Forest Process Modeling

Models provide a tool to assemble and test our understanding of forest processes. Derived from experimental studies, literature reviews and monitoring observations, models can be useful in synthesizing complex relationships between soil, atmospheric change, forest species structure and function. For this assessment, we used a well-validated forest process model called PnET-II (McNulty et al. 1996; 1997) to assess the impact of climate change on southern forests.

6.2.1.1 Methods

PnET-II is a forest process model developed to predict forest productivity and hydrology across a range of climates and site conditions (Aber and Federer, 1992; Ollinger et al., 1998; McNulty et al., 2000). PnET-II uses site-specific soil water holding capacity (SWHC) and four monthly climate parameters (minimum and maximum air temperature, total precipitation and solar radiation) along with forest specific attribute coefficients to predict changes in southern US forest net primary productivity (NPP) and drainage.

Predicted NPP is calculated as total gross photosynthesis minus growth and maintenance respiration for leaf, wood, and root compartments. Gross photosynthesis is first calculated without water stress effects as a function of temperature, foliar nitrogen concentration, and vapor pressure deficit. The optimal temperature for net photosynthesis varied from $24^{o}C$ to $28^{o}C$ depending on forest type. As temperature increased beyond the optimal photosynthetic temperature, the respiration rate increased, while gross photosynthesis increased slightly or decreased, and proportionally less net carbon per unit leaf area was fixed.

PnET-II calculated the maximum amount of leaf-area that can be supported on a site based on the soil, the climate, and tree species-specific vegetation attributes (Aber et al., 1995). The model assumed that leaf area was equal to the maximum amount of foliage that could be supported due to soil water holding capacity, species, and climate limitations (Table 6.1). Increases in atmospheric CO_2 were incorporated into the model by increasing the water use efficiency constant. As CO_2 concentration increases, the amount of CO_2 that diffuses through stomates into the plant decreases per unit of time that the stomata are open, and less H_2O diffuses out of the stomates per unit of CO_2 acquired (Aber et al., 2001). Therefore, trees would be more efficient at fixing carbon under an elevated CO_2 atmosphere. To simulate this change, a linear relationship was developed between the model's initial water use efficiency constant and doubled water use efficiency constant resulting from doubled atmospheric CO_2 (Ollinger et al. 1998).

Table 6.1 Input vegetation parameters used in PnET-II forest process model.

Parameter name	Southern Hardwood Forest	Natural Pine Forest	Plantation Pine
Light extinction coefficient	0.5	0.5	0.5
Foliar retention time (years)	1	2	2
Leaf specific weight (g)	100	210	210
NetPsnMaxA	-46	1.92	1.92
NetPsnMaxB	71.9	39.64	39.64
Folial N concentration	2.4	0.9	1.3
Light half saturation (J m^2 sec^{-1})	200	291	291
Base leaf respiration fraction	0.1	0.1	0.075
Water-use-efficiency constant	10.9	11.2	11.2
Canopy evaporation fraction	0.15	0.15	0.15
Minimum air temperature for Photosynthesis (°C)	4	4	4
Optimal air temperature for Photosynthesis (°C)	24	28	28

PnET-II also predicted forest hydrology including evapotranspiration (ET) and drainage. Annual transpiration was calculated from a maximum potential transpiration modified by plant water demand (a function of gross photosynthesis and water-use efficiency). Interception loss was a function of leaf area and total precipitation. Evapotranspiration was equal to transpiration and interception loss. Drainage was calculated as water in excess of ET and SWHC. Soil water storage was determined by SWHC, monthly ET, leaf area index, and climate. Plant water demand was dependent on monthly precipitation and water stored in the soil profile. If precipitation inputs exceeded plant water demand, the soil was recharged to the SWHC. If water was still available, water was output as drainage. Monthly drainage values were summed to estimate annual drainage outflows.

PnET model predictions of forest net primary productivity (NPP) were first derived from historic climate data to develop a historical grid at a 0.5^o x 0.5^o across the southern region. The model is then re-run with the Hadley2CMSUL general circulation model (GCM, Cullen et al. 1993) to examine the impact of changing air temperature, precipitation, and atmospheric CO_2 on potential forest productivity for each grid cell. The PnET model only predicts potential productivity because actual stand stocking is not input to the model. The relative climate change impact on forest productivity was calculated as a ratio of climate scenario productivity/ historic productivity.

Ratio values greater than 1.0 indicate that forest productivity will increase for a specific cell under climate change, while values less than 1.0 indicate that climate change will have a negative impact on forest growth. The ratio for each grid cell and year was then combined with the USDA Forest Service Forest Inventory Assessment (FIA) data of stand growth.

Individual FIA plot level historic forest volume and growth data was aggregated up to the survey unit scale for analysis. A GIS mask of the survey units was overlaid on the 0.5^o x0.5^o PnET grid of productivity ratios. A weighted average of productivity is then calculated for each survey unit based on all of the predicted PnET grid cells. This procedure results in a productivity ratio mask at the FIA survey unit scale for each year and climate scenario.

To calculate climate scenario impacts on changing forest growth, the PnET predicted FIA survey unit climate scenario productivity ratio mask is overlaid on the FIA measured historic survey unit growth data. The climate scenario growth ratio mask is used as a multiplier to those historic measured growth rates. Model predictions of growth are expressed as cubic meters per FIA survey unit per year. Using this approach, specific climate scenario years or an average of several years can be examined. For this paper, we used a 10-year average productivity change around 2040 (i.e., 2035 to 2045).

6.2.1.2 Input Data

PnET-II required site-specific soils and climate data and forest type specific vegetation attributes. PnET model inputs and predictions of forest productivity and hydrology were output at a 0.5^o x 0.5^o (40 x 40 km) grid for the southern US.

Soil water holding capacity (SWHC) derived from the CONUS-Soil dataset (Miller and White, 1998) was the only soil parameter required by PnET. The SWHC data were converted into the 0.5^o x 0.5^o grid via area-weighted averaging of the CONUS soil series SWHC polygons. No site-specific vegetation data were needed to parameterize the PnET-II model. Instead, PnET-II used vegetation variables (e.g., foliar nitrogen concentration, light extinction coefficient) specifically developed for southern tree species. These variables remained fixed by forest type across all sites and model runs. PnET-II predicted climate change impacts on plantation pine, mixed natural pine and hardwood, and hardwood forests.

6.2.1.3 Sensitivity Analysis

Only the HADLEY2CMSUL was applied to the PnET-II model. However, other GCMs predict alternative climate scenarios for the southern US. For example the

Canadian climate change scenario (Boer and Denis, 1997) suggests that the southern US will become approximately 20% drier during the next century, while becoming as warm as predicted by the Hadley2CMSUL scenario.

To determine how sensitive PnET-II model predictions were to variation in climate inputs, we developed a series of climate scenarios based on the Hadley2CMSUL climate model. These scenarios represented –2^{o}C to +4^{o}C change in minimum and maximum monthly temperature, and –20% to +40% changes in total monthly precipitation from the Hadley2CMSUL model. These scenarios were run across the southern US with data from 1995 to 2100. Our practice of using alternative variations of the same climate model (Hadley2CMSUL) differs from other studies that vary climate projections by varying the climate models. While that approach also has merit, it is difficult to pinpoint the source of differences across model projections. We chose to use the Hadley2CMSUL as the core model for our analysis and vary the extremity of two key predicted variables: temperature and precipitation to evaluate the sensitivity of PnET-II and the linked models to those critical dimensions of climate within the Southeastern U.S.

6.2.2 Changes in Southern Forest Productivity

Based on the Forest Inventory and Analysis database of weighted average of volume by forest type, hardwoods are the dominant forest type in the southern US, followed by mixed pine hardwood communities and pine plantations (FIA, 1998; Fig. 6.3).

Through a combination of climate, forest type, and soil conditions, the forest communities along the Mississippi River basin and Coastal Plain were predicted to be the most productive (as measured by NPP) under current climatic conditions (Fig 6.4). Although often inaccessible, NPP measurements of wetland ecosystems confirm that they are very productive (Burke et al., 2000) relative to upland hardwood (Boring et al., 1998) or pine (Shultz, 1997) ecosystems in the southern US. Conversely, extremely hot, dry, or shallow soil areas were predicted to have the lowest forest productivity.

Under the Hadley2CMSUL baseline climate change scenario, PnET-II predicted that the southern US will experience significant increases in forest net primary productivity (NPP) during the next century. A weighted average of forest type dominance (i.e., hardwood, mixed natural pine and hardwood forests, and plantation pine) multiplied by the net change in NPP by forest type and then summed for each grid cell shows that the greatest increases in southern NPP will occur along the north border of the southern region (Fig. 6.5).

Under current climate, southern pines are currently at or above the optimum temperature for photosynthesis for much of the southern region, while hardwood forests are either at optimum or below optimum air temperature levels. PnET-II predicted that the temperature increase predicted by the Hadley2CMSUL model could cause reductions in pine (both natural and plantation) productivity in the deep south and increase pine produivity in the northern sections of the region. The net change in total pine forest productivity would be small. Hardwood NPP was predicted to increase by 36% across the region. Although the model does not predict forest species regeneration, the large

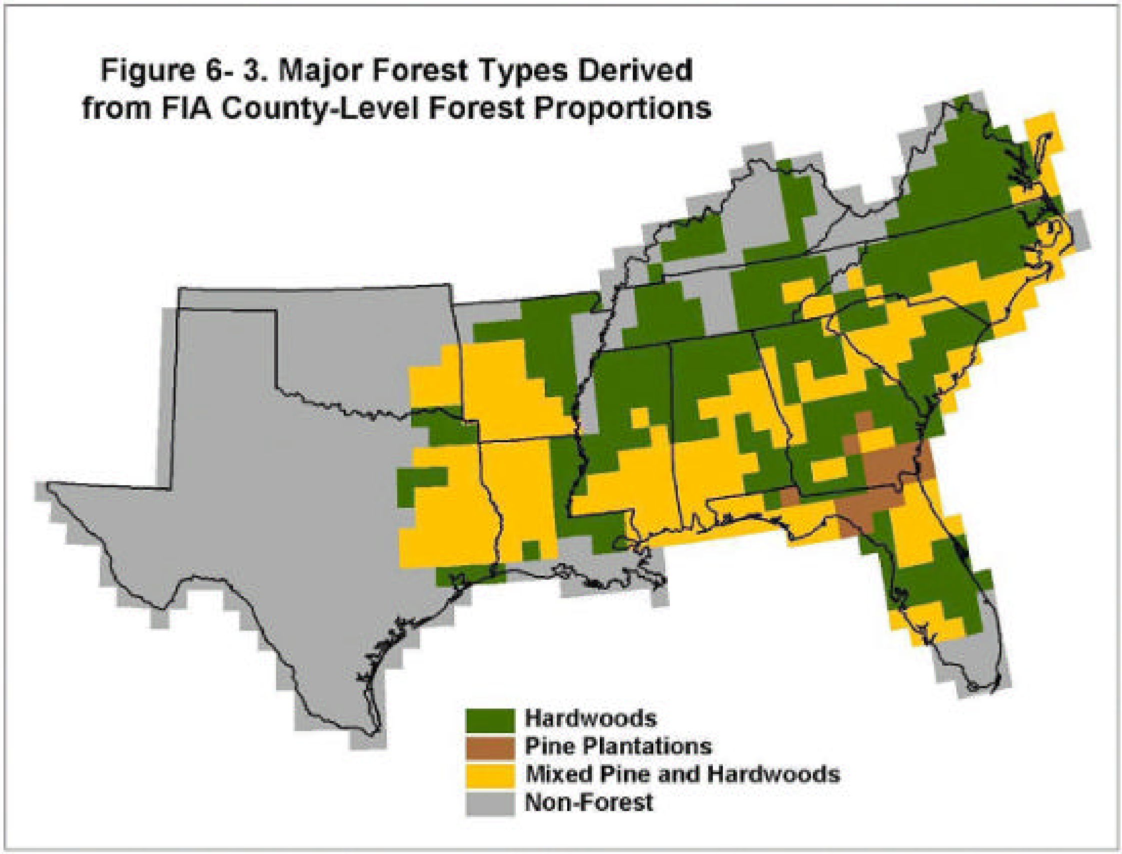


Figure 6- 3. Major Forest Types Derived
from FIA County-Level Forest Proportions
Hardwoods
Pine Plantations
Mixed Pine and Hardwoods
Non-Forest

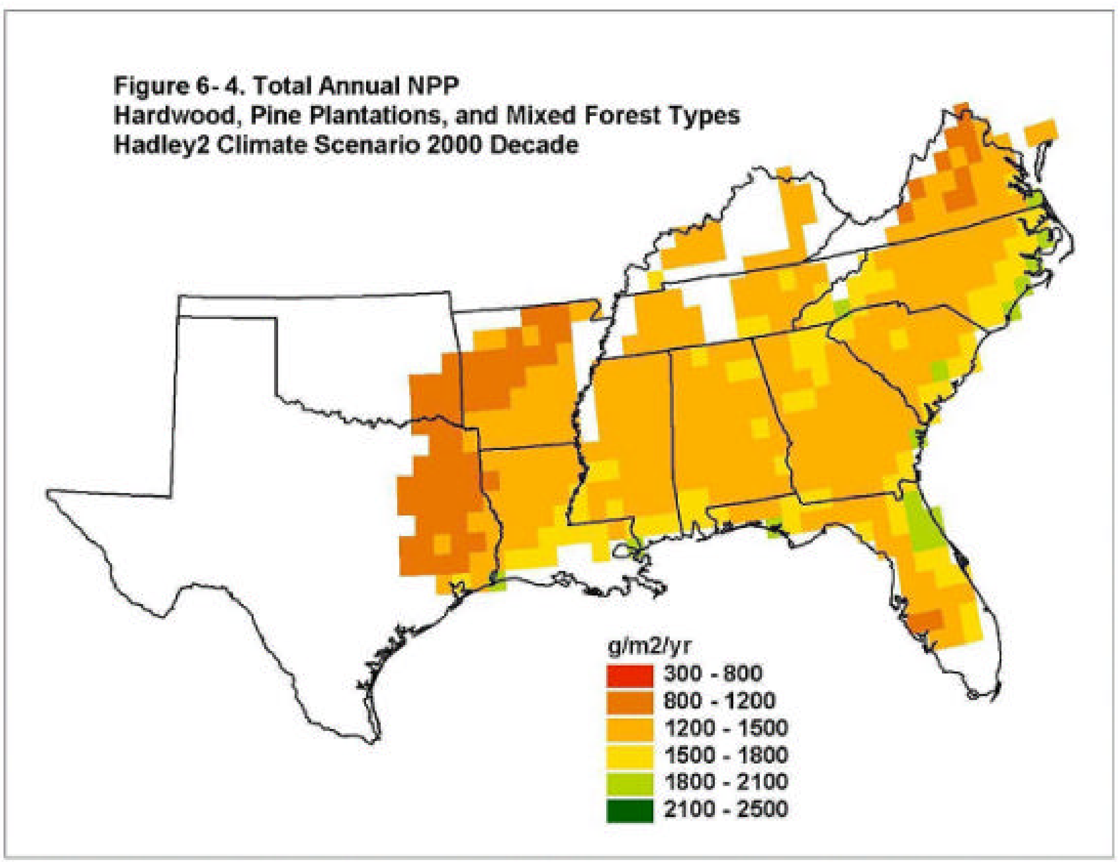
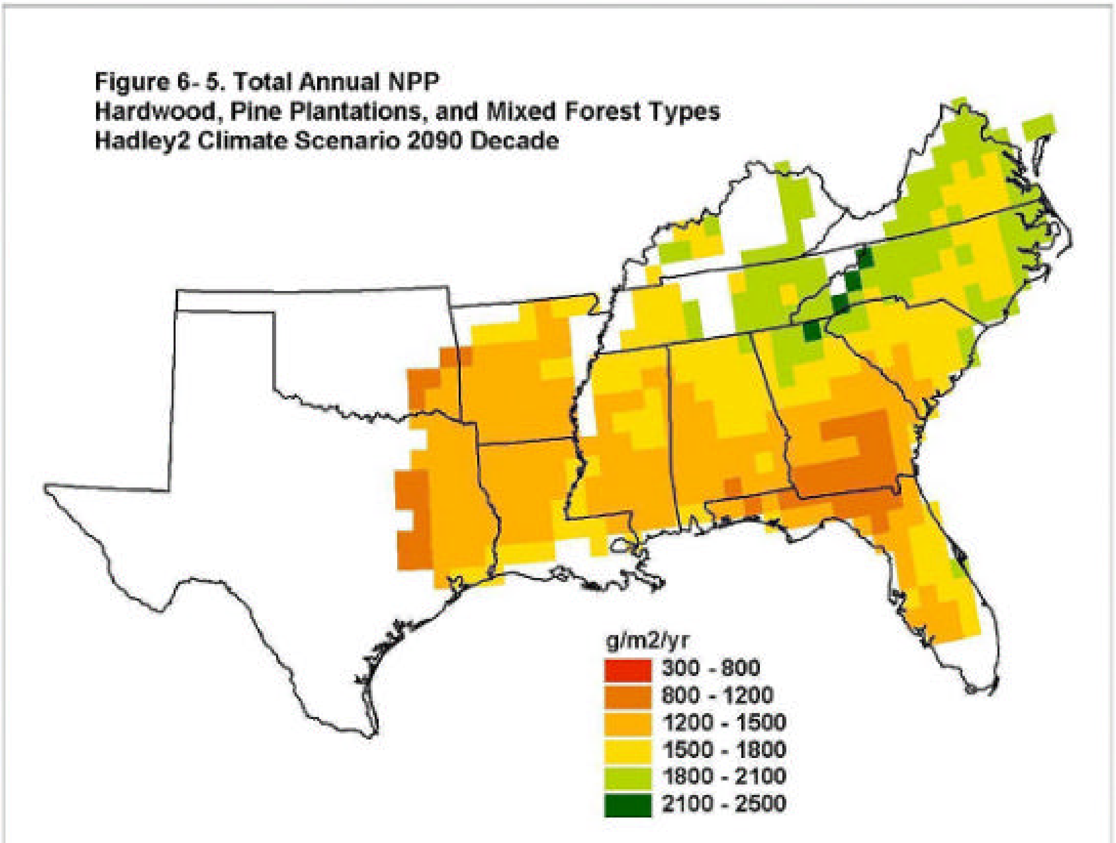


Figure 6- 4. Total Annual NPP
Hardwood, Pine Plantations, and Mixed Forest Types
Hadley2 Climate Scenario 2000 Decade
g/m2/yr
300 - 800
800 - 1200
1200 - 1500
1500 - 1800
1800 - 2100
2100 - 2500

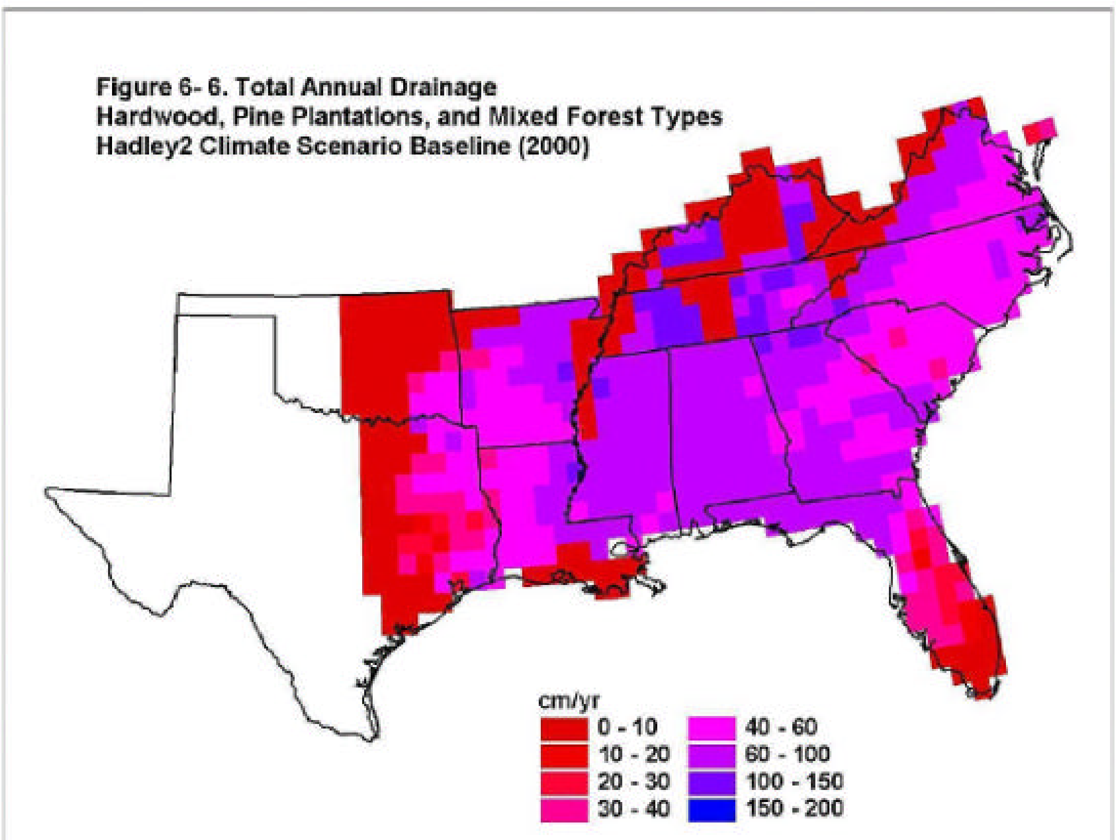


relative increases in hardwood productivity compared to pine forest productivity suggests that future hardwood forests may have a competitive advantage in species production

6.2.3 Changes in Southern Forest Water Availability

The highest rates of current drainage were predicted to occur along the southern Appalachian Mountains and southern Gulf Coast (Fig. 6.6), largely as a function of high rates of precipitation. Low rates of drainage were predicted for central Florida and eastern Texas where shallow soils, low precipitation rates, or high evapotranspiration reduce water out-flow from forests. This pattern of drainage is in close agreement with USGS measured water flow for the southeastern US (USGS, 1992).

Vegetation dynamics are tightly coupled with hydrologic processes, comprising a complex set of interactions between vegetation water use efficiency, soil characteristics, snow dynamics, and climate (Dale, 1997). Within the PnET model, water use efficiency was allowed to double with doubled atmospheric CO_2. This change required the trees to use only half of the water previously necessary to fix a unit of carbon, all other conditions being equal. However, with actual climate change, increased temperatures and a longer growing season would cause the forest to use increase water use.



The interaction between increased water efficiency, longer growing seasons, and increased air temperature can be seen in PnET-II predictions of drainage. For both planted and natural pines, drainage increased by 65% with a doubled increase in the water use efficiency constant, despite little change in total annual forest NPP (Table 6.2). Drainage from hardwood forests increased by 72% despite a 36% increase in NPP and associated increases in leaf area index.

Table 6.2 PnET-II modeled NPP and drainage predictions from climate change scenario sensitivity analysis. PP = pine plantation; MIX = mixed pine and hardwood forests; HW = hardwood forest; PPT = percentage change in average monthly precipitation; ^{o}C = celsius degree change in average monthly ground surface air temperature; NPP = forest net annual primary productivity.

	Average NPP 1990-2000 (t ha^{-1} year^{-1})			Average NPP 2090-2100 (t ha^{-1} year^{-1})			Average Drainage 1990-2000 (cm water year^{-1})			Average Drainage 2090-2100 (cm water year^{-1})		
Scenario	PP	MIX	HW	PP	MIX	HW	PP	MIX	HW	PP	MIX	HW
HadleyHadley2C MSUL baseline	13.2	12.2	12.9	13.1	11.1	17.6	61	64	50	101	105	86
HadleyHadley2C MSUL –2^{o}C	13.3	12.3	13.4	16.4	13.9	19.6	65	67	55	96	101	86
HadleyHadley2C MSUL –2^{o}C +20% PPT	13.6	12.6	14.2	16.5	14.0	19.9	86	89	74	122	127	113
HadleyHadley2C MSUL +2^{o}C	12.6	11.6	12.1	7.1	6.0	13.6	60	63	47	114	116	93
HadleyHadley2C MSUL +2^{o}C – 20% PPT	12.1	11.2	11.0	7.1	5.9	13.4	41	43	32	88	90	66
HadleyHadley2C MSUL +2^{o}C + 20%PPT	13.0	11.9	12.9	7.1	6.0	13.6	80	83	64	140	143	121
HadleyHadley2C MSUL +4^{o}C	11.8	10.8	12.9	2.5	2.1	7.7	62	65	46	125	126	111
HadleyHadley2C MSUL +4^{o}C – 20% PPT	11.2	10.3	11.0	2.5	2.1	7.6	43	45	31	99	100	84
HadleyHadley2C MSUL +4^{o}C + 20%PPT	12.1	11.0	9.9	2.6	2.1	7.7	82	85	63	151	152	139

Changes in drainage were not constant across the region. A weighed average of species dominance by drainage compared between 1990-2000 and 2090-2100 revealed that that drainage would increase across the southeastern region. Reduced plant water demand with increasing atmospheric CO_2 and increased precipitation increased drainage by 70% from 1990 to 2100.

6.2.4 Sensitivity Analysis

The HADLEY2CMSUL model provided one scenario of future climate. However, while there is a general consensus that climate change will occur, there is much less agreement as to the rapidity and range of climate change. Therefore, additional climate scenarios were developed from the Hadley2CMSUL climate scenario to the better test the sensitivity of the PnET-II model to changes in climate inputs, and to examine how alternative climate changes could impact southern forest NPP and drainage.

Due to the model doubling of the water use efficiency constant, changes in forest productivity were predicted to be much less sensitive to changes in precipitation compared to changes in air temperature. For example, if $2^{o}C$ is added to each month's predicted Hadley2CMSUL scenario air temperature (a $5^{o}C$ increase above current average monthly air temperatures by 2100), southern pine productivity is reduced by almost 50% (Table 6.2), further indicating that southern forests are currently at or above optimal temperature levels. A 20% increase or decrease in total monthly precipitation has no impact on forest NPP in conjunction with the Hadley2CMSUL model $+2^{o}C$ increase in air temperature scenario. A combination of doubled water use efficiency and reduction in leaf area under the hotter scenario has removed the 20% water limitation from the pine model runs.

The model predicted that southern hardwoods would survive much better under a Hadley2CMSUL model +2^{o}C -/+ 20% precipitation scenario. Average regional hardwood productivity increased relative to current levels and the 20% reduction in precipitation had a minimal impact on NPP. Again the lack of sensitivity can be attributed to the doubling of the water use efficiency constant.

Additional warming (e.g., Hadley2CMSUL model + 4^{o}C to average monthly air temperature) further reduced pine forest productivity to approximately 20% of its current level (Table 6.2). Hardwood productivity was also severely reduced under this scenario to 60% of its current value. For reasons previously discussed, a 20% change in precipitation had little impact on forest growth.

Patterns of drainage follow those observed for the baseline Hadley2CMSUL climate scenario. Pine forests use less water than do hardwoods, largely because of reduced leaf area. Increased air temperature causes reduced leaf area and offsets increases in water loss per unit of leaf area, so average total evapotranspiration decreases and drainage increases for the region.

The output of the forest process simulations forms the basis for the economic assessments of forest product markets in the Southeast. The next section summarizes these economic analyses.

6.3 Forest Economics

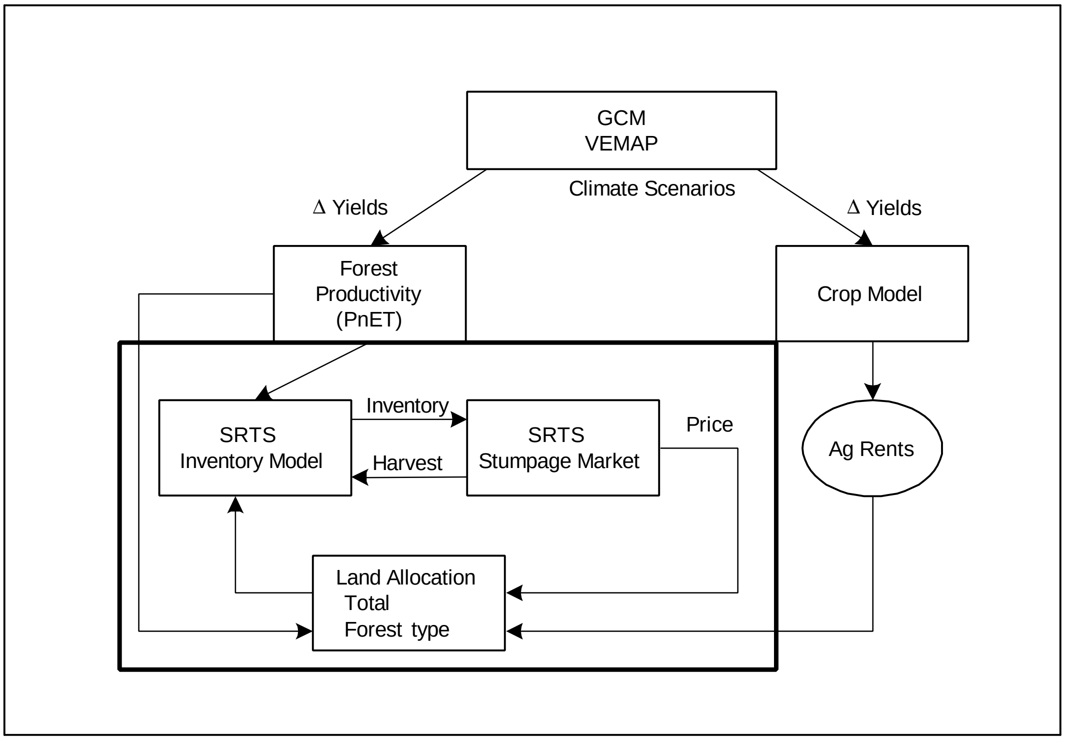
6.3.1 Historical Perspective

Over the last 50 years, hardwood and softwood inventories have increased in the South. The latest cycle of surveys in the South, however, indicate that softwood removals slightly exceed growth for the region as a whole. Hardwood removals are currently 30% below growth, but if current removal trends continue, hardwood inventory could peak in the next decade. With increases in removals in the late 1980's, stumpage and lumber prices have also increased dramatically (Haynes et al., 1995). Though the ecosystems are predominately hardwood or mixed pine types, the softwood resource has been traditionally managed more intensively, with approximately 20% of timberland managed as pine plantations. Hardwood markets, however, have exhibited the greatest percentage increase in removals and prices over the last decade.

6.3.2 Potential Climate Change Impact

The ultimate impact of climate change of the forest ecosystems of the South is likely to depend as much on the response of landowners and wood consumers as on the physical changes due to climate. The South is the home of the most active competitive market for forest products. Market forces exert a powerful buffering force to resource changes in many ways. As resources become scarce, resource users will have incentives to substitute other products or develop technologies to become more efficient. The modeling approach employed here attempts to capture the major market adjustments likely to affect the future of the southern resource. The market adjustments included in this system are shown in Figure 6.7. They include, 1) empirically-based price and harvest adjustments in the aggregate market, 2) management response as reflected in plantation growth rates and acreage, and 3) spatial shifts in harvest to reflect variations in regional supply due to climate, ownership, forest types, and land use change. The biological growth model and climate change scenarios are described in Section 6.2. The land use module is discussed in Section 6.4.

Figure 6-7. Overview



Forested ecosystems cover over one-half of the land area of the South and are an integral part of the culture and economy of the region. Ninety percent of the forest resource is owned by private landowners with a variety of objectives (Moulton and Birch, 1995). Forest-based industry owns almost one-fourth of the timberland in the area. These industries are a significant component of the southern economy where the value of timber products exceeds agricultural crops in most states. The resource is also a critical and growing component of the U.S. timber economy since approximately 40 percent of the timberland and almost half of the removals (softwood and hardwood) are located in the region (Powell et al. 1994).

Sub-Regional Timber Supply (SRTS, Abt et al. 2000) model projections indicate that intensive management responses may increase growth enough for the softwood inventory to stabilize within the next decade, even with increasing demand. There are, however, limited options for intensive management on hardwoods. This competitive economic context implies that even marginal climate changes in the next 50 years may significantly influence the sustainability of current harvest levels. While management-based adaptation may be realistic for pine types, the passive management associated with hardwoods implies that ecological adaptation may be more important for hardwoods.

6.3.2.1 Methods

SRTS was developed to provide consistent methodology for examining the impacts of shifts in regional demand on sub-regional supply (Abt 1989). The inventory model is based on detailed data for inventory, area, growth, and removals by 48 supply regions (survey units), 2 ownerships (industry and non-industrial), 2 species groups (softwood and hardwood), 5 forest types (planted pine, natural pine, mixed pine-hardwood, upland hardwood, and lowland hardwood), and 10 year age classes.

The timber market, biological inventory, and land use modules make up the SRTS model applied here. Land area modeling is described in Chapter 6.4. Market parameters are first used to solve for equilibrium price changes, where the market is defined by all of the included subregions. Second, the price and supply shift information from the individual regions and owners is used to calculate harvest change by subregion. For the analysis presented here, FIA survey units and industry and other private ownerships in the South are used to define 98 (49 units x 2 owner types) subregions in the model. Public lands and harvest, which are less than 10 percent of the regional total, are excluded from the model because short-run markets do not drive their harvest and management decisions.

The standard SRTS structure was described in Abt et al. 2000. It was modified for this application by using the PnET model estimates of changes in growth due to climate change (McNulty et al 2000). This change was applied to empirical estimates of current growth in SRTS. For plantations, the change was assumed to apply to the baseline increases in growth due to genetic improvement and changes in silvicultural techniques. The implementation of the land use model (Section 6.4) allowed both aggregate timberland and pine plantation acreage to respond to changes in prices. The land use model allowed changes in demographic trends and agricultural rents to condition timber supply.

Beyond the sensitivity to climate change scenarios described in McNulty et al. 2000, extensive model runs were made to investigate sensitivity of results the following economic assumptions.

The baseline demand trend followed the USDA Forest Service projections for the South for the years 1990 to 2020 (Haynes, et al. 1995). Beyond 2020, demand was assumed to increase linearly at 3 percent per year until 2040. An alternative low demand scenario was considered where demand increased linearly at 1 percent per year.

Empirical estimates indicate that demand for forest products is inelastic (Adams and Haynes 1996, Newman 1987.). This implies that shifts in supply would have large price effects and small harvest effects. While this may be an accurate estimate of derived demand, it may not be the most appropriate to model global phenomena. Given the recent globalization of markets and the fact that climate change is not likely to affect all species and markets equally, it seems unlikely southern supply effects will, ceteris paribus, lead to large price swings in global markets. It is more likely that there will be regional shifts globally, similar to the internal assumptions used for SRTS in the South. To reflect the uncertain nature of the demand assumptions, three demand elasticities are used, inelastic (.5) to reflect lack of harvest adjustment possibilities, elastic (5) to reflect extensive adjustment, and very elastic (50) to simulate global prices unaffected by changes in the southern resource. The elasticity estimate of 5 reflects the southern influence on national prices and is used for the price scenarios discussed below.

After the exploitation of the southern forest resource during the early twentieth century, the southern resource was largely devastated. After technological breakthroughs in the 1940s and 1950s, industrial forestry focused on pulp production expanded. The primary focus of industrial silviculture has been pine plantations. Recent studies suggest that pine growth rates may double through the application of genetic improvement, fertilization, and herbicides. Advances in growth in research plots, however, do not directly correlate with region-wide change. The base assumption on plantation growth rates was an increase of 80 percent on industrial lands by 2040, and an increase of 40 percent on non-industrial lands. Simulations were also performed with +/- 50 percent of the base growth assumption. The price responsiveness of acres planted is described in section 6.4.

The climate change sensitivity analyses discussed in Section 6.2 were also used as inputs into the integrated model system. These runs were conducted with a demand elasticity of 0.5. Since agricultural markets were not explicitly modeled and agricultural income estimates were not available for all climate scenarios, a set of runs were conducted in which agricultural income was held constant.

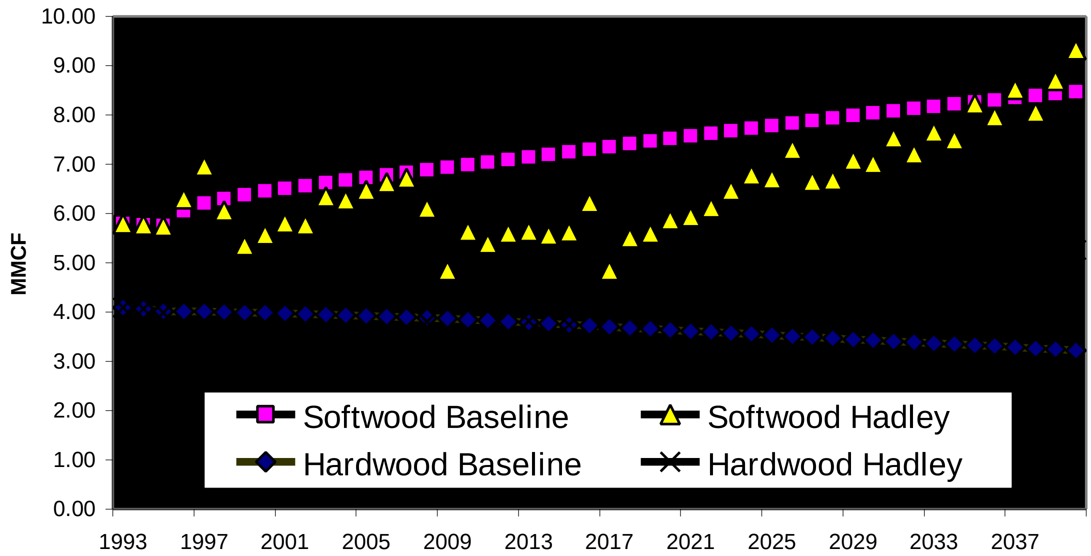
6.3.2.2 Results

The results are categorized into four sections, growth inputs, inventory characteristics, spatial variation, market parameters, and sensitivity analysis.

Figure 6.8 shows the baseline and Hadley2CMSUL growth trends for the entire south by species group. The baseline growth trend for softwoods shows an upward trend due to the increases in plantation acres and the growth increase experienced on those acres. The baseline hardwood trend shows a gradual decrease over time due to the loss of hardwood acres, either to other land uses or to planted pine, and changes in growth rates due to age structure. These long-term trends are based on the empirical estimates of current growth and projected management and land-use trends.

The influence of Hadley2CMSUL climate on aggregate growth in Figure 6.8 shows in both the annual variability and long term trends. These regional averages mask

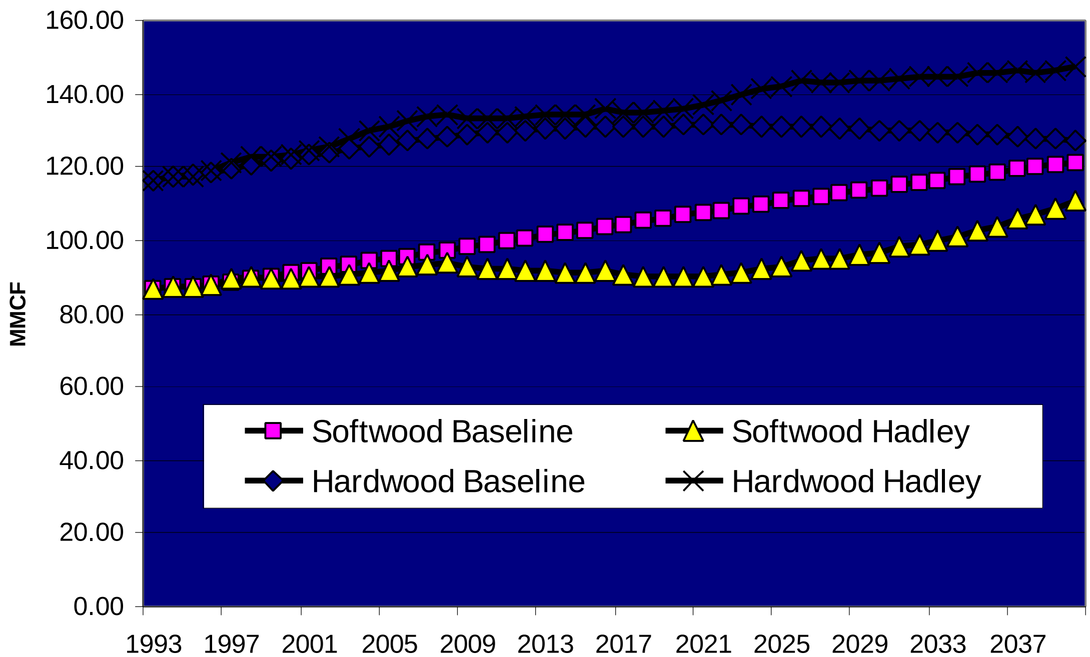
Figure 6.8. Baseline and Hadley Growth Trends



significant variability across the South. For both species groups, there is a pronounced growth decline in the 2010 to 2020 decade. For hardwoods, this is the only period where the Hadley2CMSUL trend is on average below the baseline trend. For all other periods, future hardwood productivity is greater than historic productivity. For softwoods, the Hadley2CMSUL scenario is on average below the baseline reflecting a decrease in softwood growth during the early decades. During the 2030 to 2040 period, however, softwood growth meets or exceeds baseline growth. Regional trends show up to 20 percent higher growth rates in the mid-Atlantic states as compared to the Gulf states. McNulty et al. 2000 discusses the differential effect of climate change on species groups.

While the variability in annual growth estimates is significant, annual growth is only 3 to 5 percent of inventory. The annual fluctuations do not significantly affect inventory variability, as shown in Figure 6.9. This is partially due to the cumulative nature of inventory, and also due to harvest response induced by changes in supply

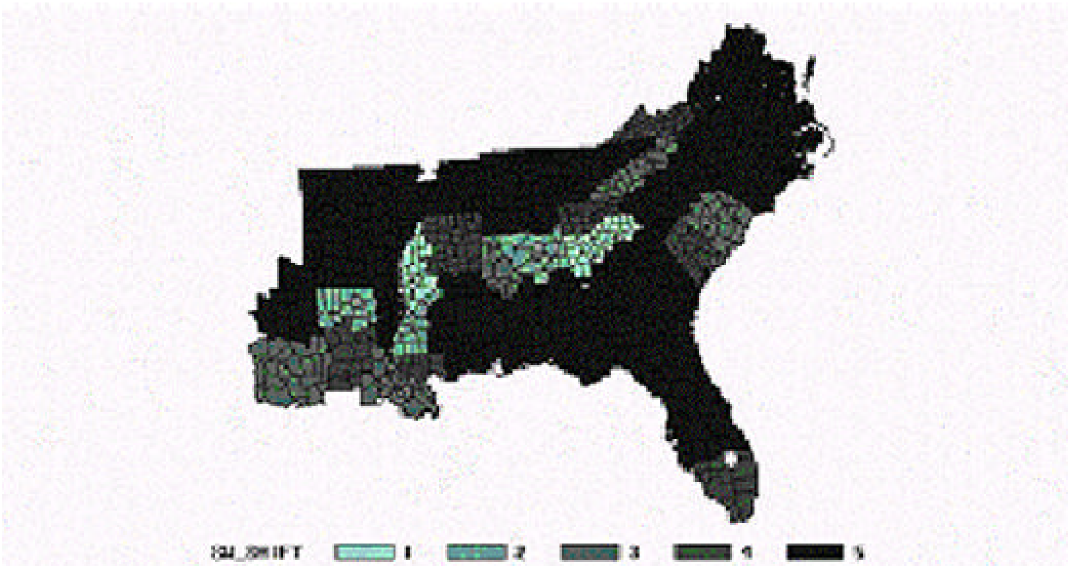
Figure 6.9. Baseline and Hadley Inventory Trends



(Figure 6.15). The overall inventory trend shows the impact of the growth decrease in the middle decades followed by a recovery toward the end of the projection period. Southwide hardwood growing stock inventory under Hadley2CMSUL is always higher than the baseline, while softwoods are always lower (Figure 6.9).

Spatial variation in growth is discussed in Section 6.2. Spatial variation in softwood inventory resulting from the interaction of growth, harvest, and land use is shown in Figures 6.10-6.12. Figure 6.10 shows that over the baseline projection period softwood inventory increases in the plantations of the coastal plain. Current South Carolina data (1993) are influenced by increased mortality from Hurricane Hugo. When growth data are adjusted the South Carolina coastal plain experiences inventory increases consistent with other southern states. Figure 6.11 shows that during the softwood growth decline from 2010 to 2020, overall inventory decreases slightly (Figure 6.9) as is shown

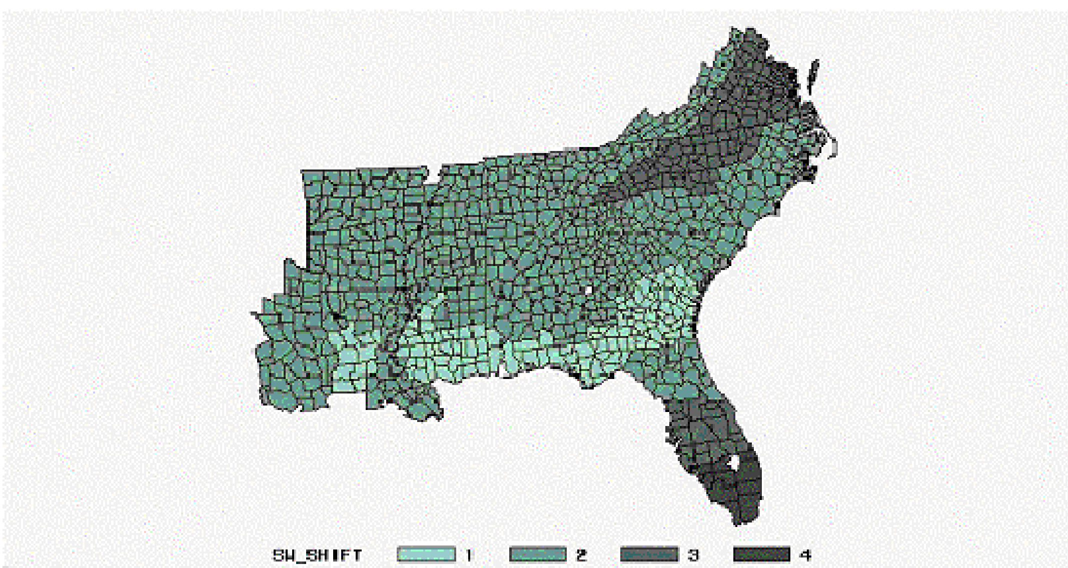
Figure 6.10. Softwood Inventory Shift – Baseline 1990 to Baseline 2040



>25% <25% <5% <25% >25%

DECREASE NEUTRAL INCREASE

Figure 6.11. Softwood Inventory Shift - Baseline 2020 to Hadley 2020



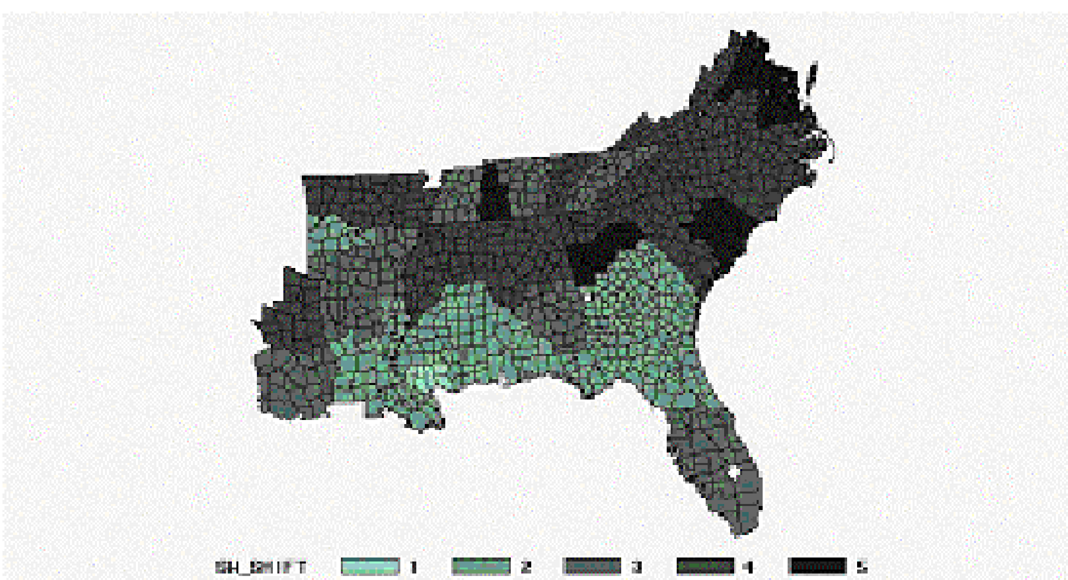
>25% <25% <5% <25% >25%

DECREASE NEUTRAL INCREASE

by all regions having decreases in inventory as compared to the baseline. Relative declines are smaller in the mid-Atlantic region. Figure 6.12 shows that by 2040 inventory has recovered with climate change causing a slight northward shift in the concentration of softwood inventory.

The baseline hardwood results show an increase in hardwood inventory during the beginning of the projection period, followed by a gradual decline as increased demand leads drive aggregate harvest above aggregate growth. Figure 6.13 shows that inventory increases are concentrated in the less accessible mountain and lowland hardwood regions of the South. Relative to the baseline, the Hadley2CMSUL scenario increases hardwood inventory through most of the South, with a slight relative decline in the Gulf region (Figure 6.14).

Figure 6.12. Softwood Inventory Shift - Baseline 2040 to Hadley 2040



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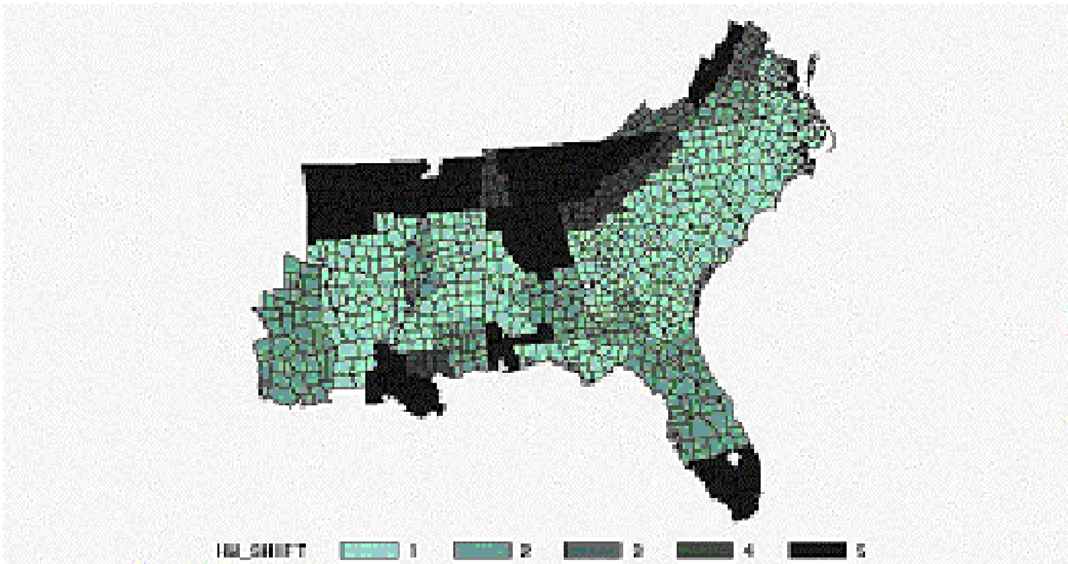
DECREASE NEUTRAL INCREASE

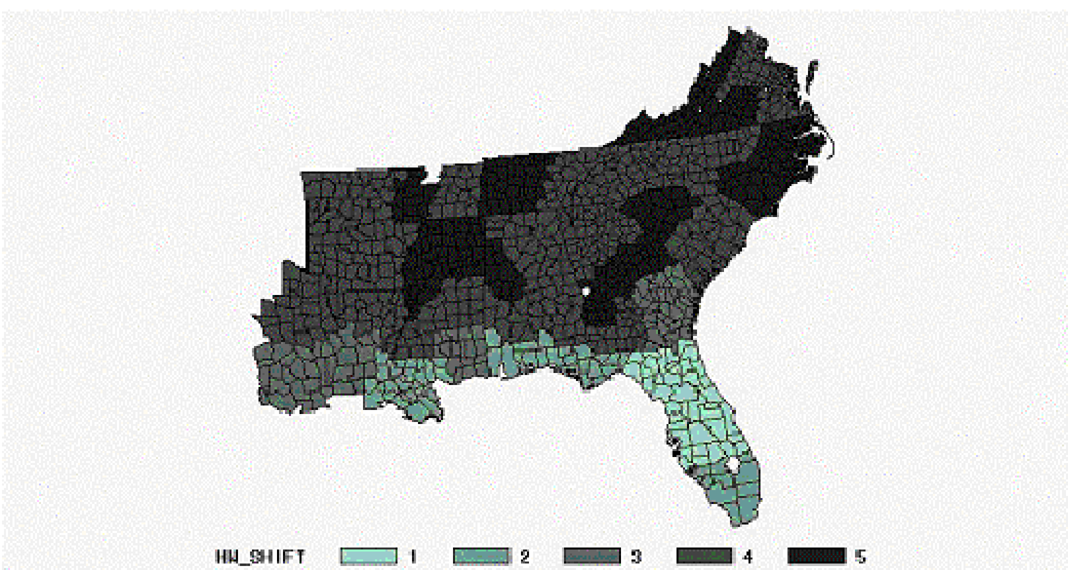
Figure 6.13. Hardwood Inventory Shift - Baseline 1990 to Baseline 2040



>25% *<25%* *<5%* *<25%* *>25*

DECREASE NEUTRAL INCREASE

Figure 6-14. Hardwood Inventory Shift - Baseline 2040 to Hadley 2040

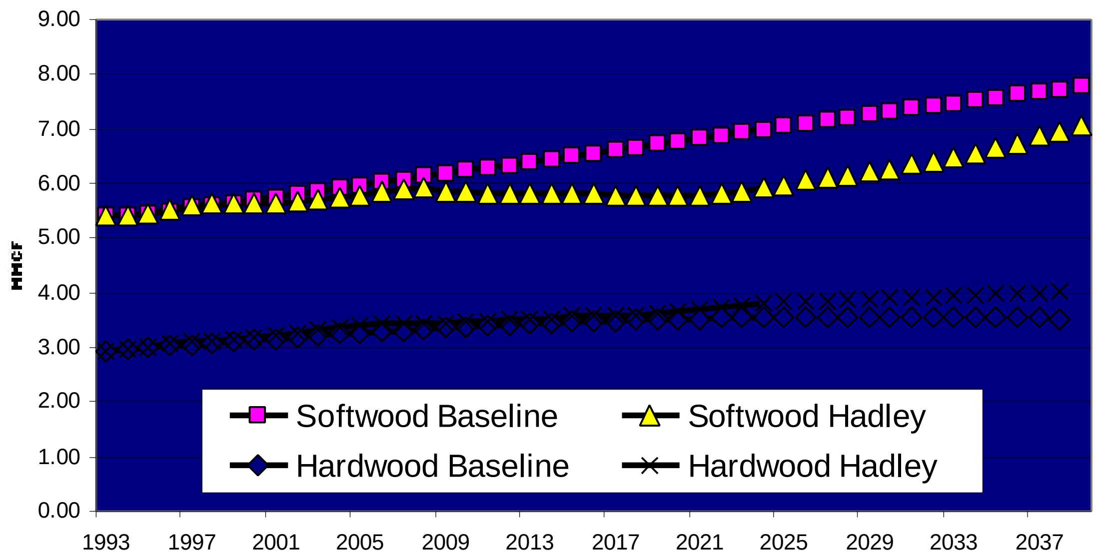


>25% *<25%* *<5%* *<25%* *>25%*

DECREASE NEUTRAL INCREASE

Figure 6.15 shows how harvest levels adjusted to climate induced inventory changes. Since demand is elastic (5), most of the adjustment to supply changes comes from harvest reduction rather than price increases. This buffers the impact of growth changes on inventory in the aggregate, and also induces regional shifts in harvest that reduce spatial variation in inventory trends.   During the decades of low projected softwood growth, softwood removals level off even with the assumed increases in demand. In the last decade of the projection, removals recover as growth recovers (Figure 6.8), but never reaches baseline levels. For hardwoods baseline removals remain relatively level despite increased demand due to inventory declines. Under the Hadley2CMSUL climate, hardwood removals continue to increase throughout the projection period.

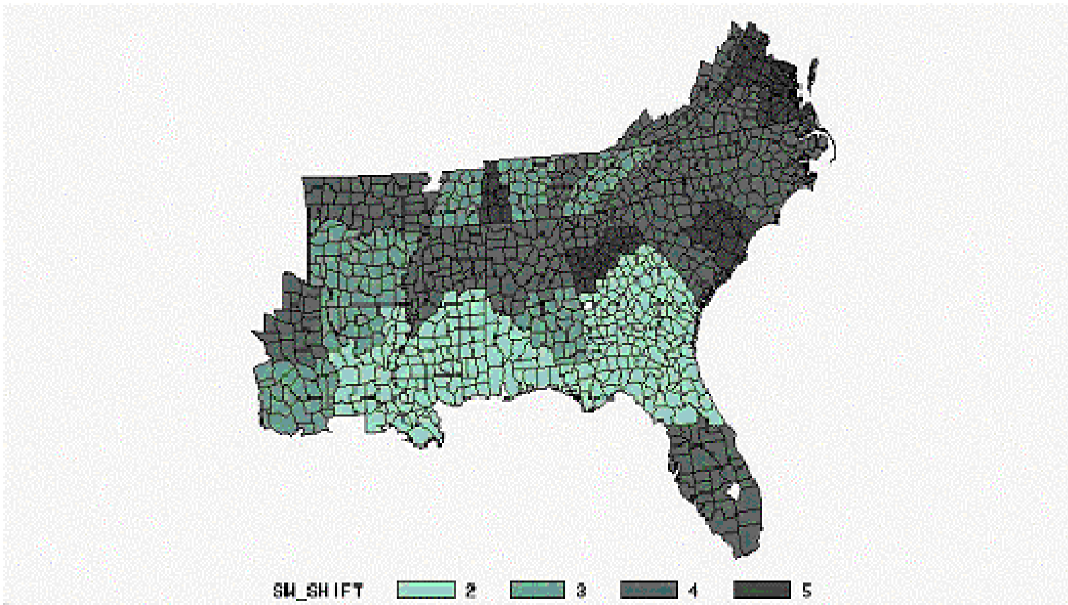
Figure 6.15. Baseline and Hadley Removal Trends



Figures 6.16 and 6.17 show the sub regional removal adjustments to climate change induced changes in inventory. For softwoods removals are reduced in the gulf coast states and increased in the mid-Atlantic. For both scenarios, however, there is increased concentration in softwood removals on plantations in the coastal plain. Since climate change reduces softwood growth, the aggregate level of softwood removals is lower in the Hadley2CMSUL relative to the baseline (Figure 6.15). For hardwoods (Figure 6.17) the shifts are more generally northward with increases in Tennessee, the northern portions of Mississippi, Alabama, and Georgia, and the mid-Atlantic region.

Figure 6.18 shows the softwood and hardwood price trends from baseline, Hadley2CMSUL, and two climate sensitivity runs. The Hadley2CMSUL scenario increases softwood prices slightly and decreases hardwood prices relative to the baseline, which is consistent with their aggregate affect on growth rates and inventory. Since demand is elastic, the price influences are subtle relative to the quantity (harvest) impacts. Figure 6.19 shows the more extreme climate scenarios have dramatic negative impacts on growth and inventory. These scenarios are discussed in detail in Section 6.2. While both hardwood and softwood inventories decline from the baseline, the pure biological effects are partially ameliorated by a reduction in harvest. Softwoods appear especially vulnerable to the hotter and drier climate simulated. The regional comparative advantages continued in the alternative climate scenarios with drastic mortality experienced in the Gulf states and relatively smaller effects in the mid-Atlantic region. These shifts led to even more dramatic regional differences in harvest levels across the southern latitudes.

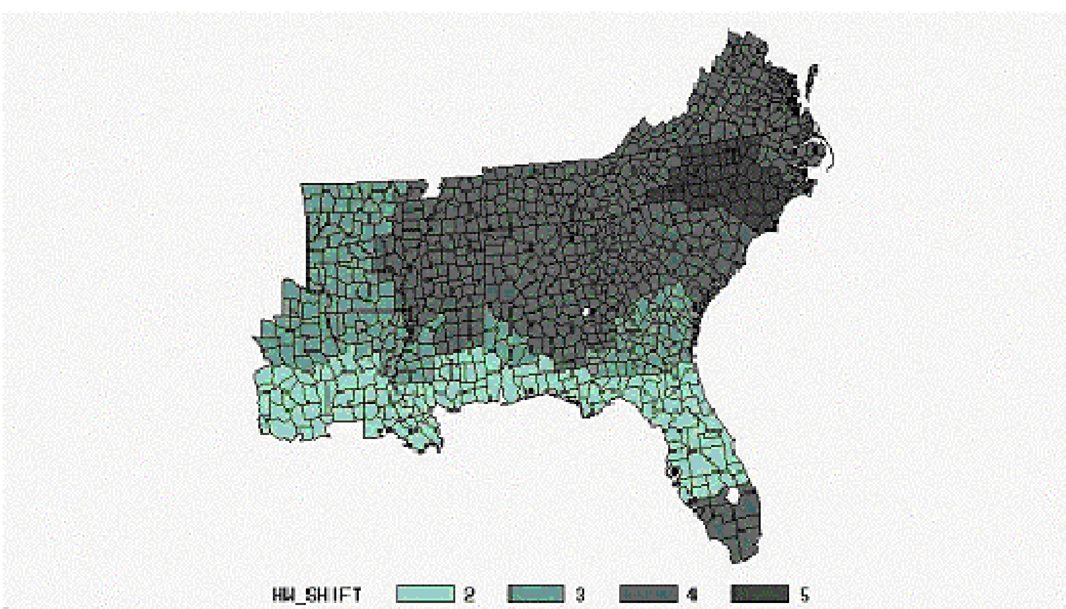
Figure 6- 16. Softwood Removal Shift - Baseline 2040 to Hadley 2040



>25 *<25%* *<5%* *<25%* *>25*

DECREASE NEUTRAL INCREASE

Figure 6- 17. Hardwood Removal Shift - Baseline 2040 to Hadley 2040



>25% *<25%* *<5%* *<25%* *>25%*

DECREASE NEUTRAL INCREASE

Figure 6.18. Price Trends By Climate Scenario

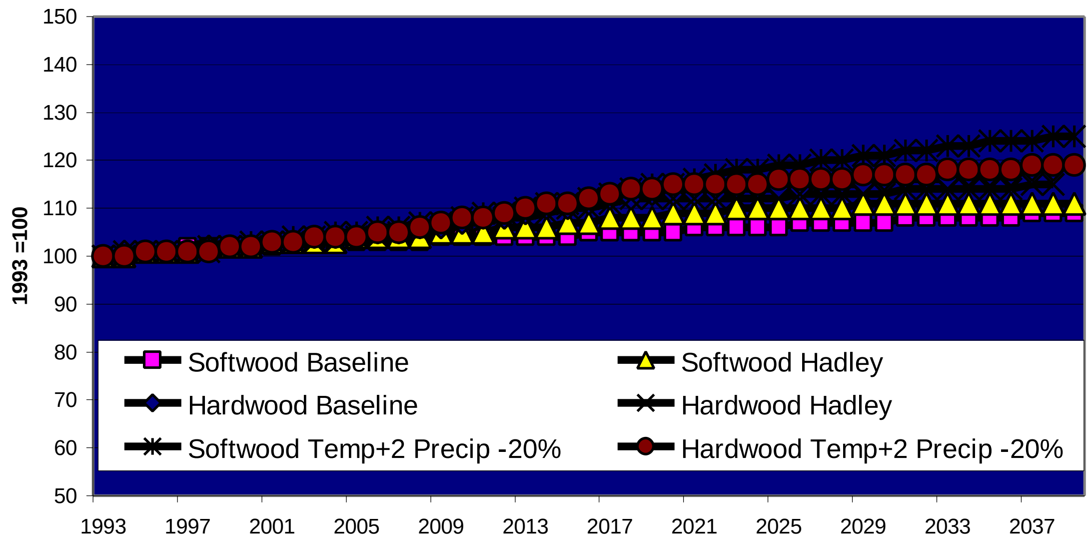
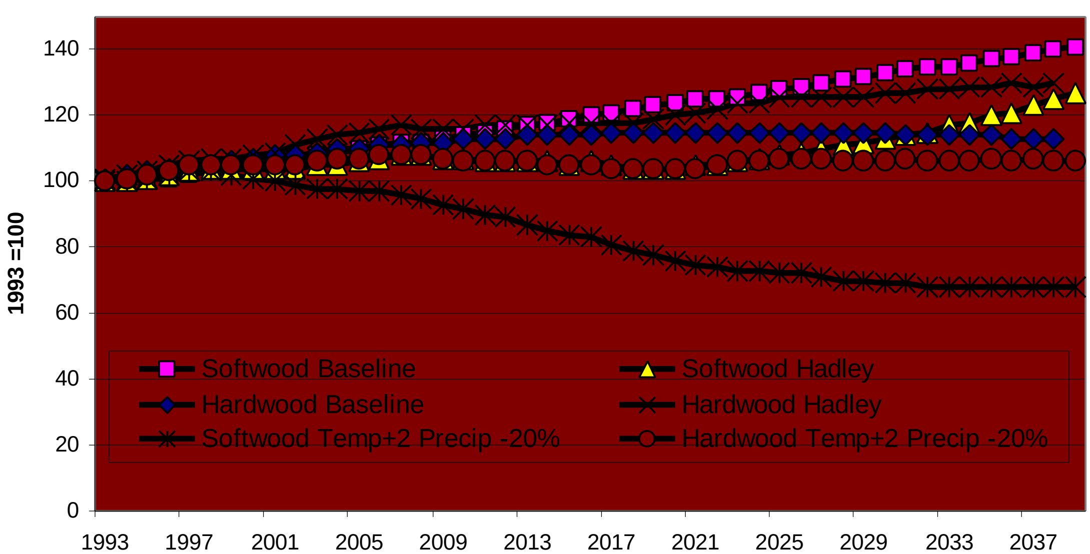


Figure 6.19. Inventory Trends By Climate Scenario



The focus of this analysis is modeling the intra-regional adjustments of timber and land markets in the U.S. South to the Hadley2CMSUL II climate change scenario. The adjustments include changing levels and distribution of harvest across ownerships, forest types, and age classes within the South. Both the Hadley2CMSUL scenario and historical data indicate relatively large fluctuations in annual growth rates. The cumulative nature of inventory tends buffer these short-term fluctuations in annual growth and removal rates. When market adjustments are coupled with relatively benign inventory impacts, the net impact on timber markets tend to be subtle changes in aggregate harvest levels and prices with a slight northward shift in harvest pressure. Since the market mechanism allows harvest to respond to changes in inventory the spatial re-distribution of harvest reduces the eventual impact of changes in growth rates on inventory.

Sensitivity analysis indicates that more severe climate scenarios could lead to much more dramatic effects. The more dramatic changes are beyond the capability of empirical models to assess. Changes in species mix or dramatic increases in mortality will cause structural changes in both the ecological and economic systems. Empirical models may provide insight into the nature and time-scale of structural change, but may not correctly characterize the response to major changes.

Modeling a global long-run phenomenon like climate change with a regional empirically-based modeling system has certain conceptual advantages (intra-regional detail) and someobvious conceptual disadvantages (omitted inter-regional feedback). The model can only assess interactions with other regions through exogenous shifts in regional demand. Given the ecological detail being modeled within the South, it would have been impossible to employ a symmetric approach globally. Global studies have the advantage of analyzing global comparative advantage but are limited with respect to intra-regional detail (Sohngen and Mendelsohn 1998, Perez-Garcia et al. 1997). Further, while our empirical econometric modeling approaches tends to do a better job of modeling current behavior and, by extension, marginal changes in current behavior than models based on "optimal" behavior, they may not be appropriate for modeling structural change. Our approach of using empirical models of revealed behavior is especially important for modeling the behavior of non-industrial private landowners, who control a large majority of the resource being managed in the Southeast U.S. Given the subtle nature of short-term changes in climate change, the econometric approach may provide a better platform for assessing actual adjustments rather than optimal adjustments. Both modeling approaches are necessary to address the range of policy issues across temporal and spatial scales.

6.4 Land Use Change

6.4.1 Historical Perspective

Forests and agriculture are the predominate uses of land in the southeastern U.S. Because much of the region's topography is well-suited to both uses, the momentous changes in economic forces that affect land use have caused a substantial amount of land to move between forest and agriculture over the last century (Healy, 1985). In the Southeast, land is almost exclusively owned by private parties and its use is thereby influenced by market forces that determine the returns to alternative land uses. In this assessment, we see how climate change may affect the economic returns to agriculture and forests and thereby alter the allocation of land to those uses. Changes in land use have broad implications for the socio-economic and environmental services provided by the region's land base. Moreover, land use change can have feedback effects into climate change by modifying the amount of greenhouse gases (particularly CO_2) that are emitted to the atmosphere and the amount of carbon that is sequestered in terrestrial sinks (IPCC, 2000).

6.4.2 Potential Impacts of Climate Change

6.4.2.1 Methods for Economic Modeling of Land Use Change

Because most land in the southeastern US is under private ownership, its use is largely determined in a competitive land market setting. As a result, a properly structured econometric model can be used to simulate land allocation within the region. Econometric studies of the private allocation of private land in the southern US includes studies by White and Fleming (1980); Alig (1986); Alig et al. (1988); Hardie and Parks (1997), and Hardie et al. (2000). The last of these studies provides the empirical foundation for the land allocation model in this assessment.

Climate affects the physical growth processes that determine agriculture and forestry economic returns (land rents). Changes in economic returns affect the way land is allocated on the margin. For instance, if climate changes the relative returns to forest and agriculture, then it will cause some land to shift from the relatively less profitable to the relatively more profitable use. This occurs regardless of whether the absolute changes in productivity are positive or negative. Changes in land use alter the supply conditions of the respective commodities. Movement of land from agriculture to forestry, for instance, would expand the (long-run) supply of timber and other forest commodities, but would contract the supply of agricultural commodities. Depending on the characteristics of the affected commodity markets, this may change the relative prices of the commodities, which further alters the relative returns to the uses and the incentive for marginal land use changes. This process continues until an equilibrium is reached between the land and commodity markets.

Many variables determining land use (population, income, housing values) are largely determined by forces external to the processes modeled within the integrated modeling system and are thereby treated as exogenous variables to the system. Data projections for those demographic variables are obtained from NPA (1999). Other determining variables (timber prices, agricultural income) are endogenously determined within the system. Therefore, our objective is to link timber and agricultural markets to the land market through the latter endogenous variables. Thus, the timber price and agricultural income effects induced by the climate scenarios, along with the exogenous demographic data projections, are fed into the land use model to simulate the resulting changes in land use. The land allocation solution is then fed back into the timber market model, thereby affecting long-run supply conditions and prices there, which are then fed back into the land model on a recursive basis. Similar feedbacks on the agricultural side are not included because regional agricultural commodity markets are not modeled in this assessment. Potential limitations of this exclusion are discussed below.

How sensitive are changes in land use to commodity market returns? Hardie et al. (2000) estimated land use elasticities (i.e., the proportional change in equilibrium land allocation with respect to a proportional change in timber price) for forestland in the range of +0.35. This indicates that a 10% rise in timber prices would generate a roughly 3.5% increase in timberland, holding all other variables constant. This elasticity is in the same range as those found in the other studies of southern US land use referenced above, though is higher (more responsive) than estimates found in other regions (Parks and Murray, 1994).

Climate change can also affect the incentives for intensive forest management. In the Southeast, forest owners can either expend resources to establish and maintain plantations, generally of pine, or allow forests to evolve largely through natural processes. The former approach causes a forest stand to reach its economic optimum at an earlier age, but is more costly. Therefore, plantations are more economic when prices are high and the associated productivity gains are large. To the extent that climate change affects timber prices and plantation growth rates, it can change the incentives to establish plantations on forested land. We model the effects of timber price and productivity changes on the allocation of forested lands between planted pine and other types using methods described above and presented in more detail in Murray et al (forthcoming).

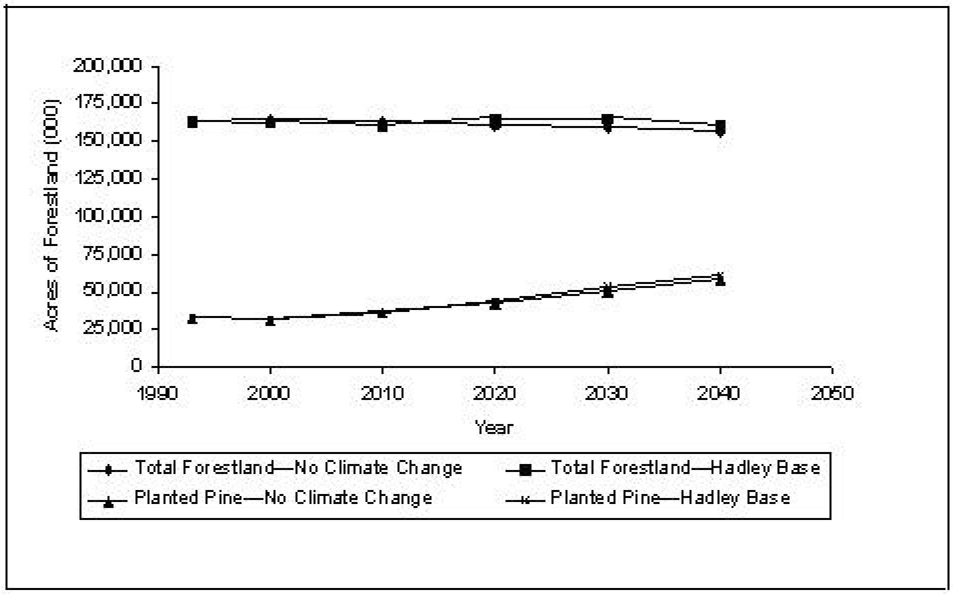
6.4.2.2. Results

Land use simulations are performed for various scenarios in the timber market analysis discussed previously. The model is capable of simulating all three major land uses (forest, agriculture, and urban/other) simultaneously; however, the forest area projections are the focus of the discussion here. Figure 6.20 features the model simulations of forest area outcomes under the no climate change baseline and under the base Hadley2CMSUL climate change scenario. The baseline (no climate change) model simulation: (1) captures feedback between the timber and land markets, (2) incorporates demographic variable projections, and (3) holds agricultural revenues and costs constant at base year values.

Under the no climate change baseline, the total area of forest is projected to remain fairly constant over the period 1993-2010. Slight gains in forest are projected in the first two decades as forest incentives (rising timber prices) just offset the demographic factors inducing conversion to developed use. Thus forest losses to developed uses are being essentially replaced by forest gains from agriculture. Beyond 2010, a net decline in forestland is projected as the rising timber inventories cause timber prices to flatten, thereby reducing forestation incentives. Meanwhile, population and income are still projected to increase and place pressure on forest conversion.

Model simulations under the Hadley2CMSUL base scenario project forestland area to fall below the baseline for most of the first two decades, as the (softwood) productivity

Figure 6- 20. Forestland Simulations: Hadley Base vs. No Climate Change



decline reduces the marginal profitability of forest as a land use. However, the rise in prices occasioned by climate-induced fall in timber inventory begins to dominate the forest productivity losses in the middle decades of the projection period. Moreover, during the middle decades, the softwood productivity losses start to turn into gains in the more northern parts of the region. Together this leads to a net gain in forest area between 2010 and 2030 under the Hadley2CMSUL base scenario. Between 2030 and 2040, timber prices start to come back to baseline levels and, as a result, net forest area begins to decline. It is noteworthy that total forest area in 2040 evolves to virtually the same level under the Hadley2CMSUL and baseline scenarios.

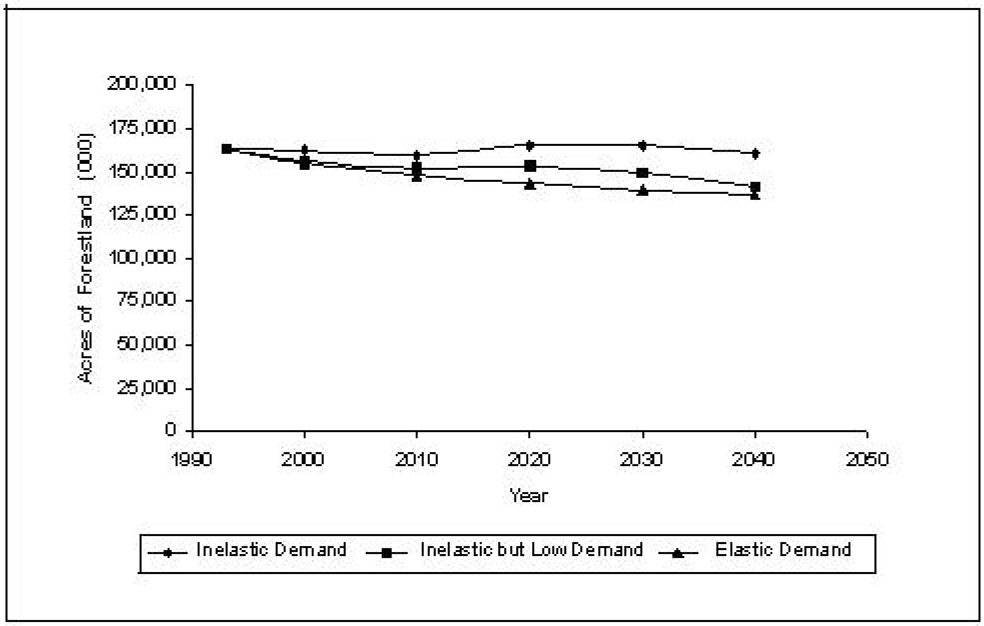
Also included in Figure 6.20 are simulated projections of pine plantation acreage under the no climate change baseline and the Hadley2CMSUL base scenario. The first thing to note is that acres planted in pine are projected to roughly double over the projection period under both scenarios. This continues the current trend of the region's natural pine and mixed hardwood forests being converted steadily to plantations and is driven in part by rising softwood timber prices. At first, planted acreage under the Hadley2CMSUL scenario is slightly lower than baseline, but beyond 2020, the continued rise in prices, coupled with climate-induced improvements in site productivity cause the Hadley2CMSUL scenario planted acres to modestly exceed baseline levels.

6.4.2.3 Sensitivity of Results to Variations in Timber and Market Demand Scenarios

As discussed previously, our base assumption is that demand for Southeastern timber is fairly inelastic (elasticity value of -0.5) and that timber demand will grow roughly at the rate of the population. The model simulations include variations on the demand elasticity assumption to capture more elastic demand for southeastern US timber due to substitution with timber from other regions (that may be more or less favorably affected by climate impacts on forest productivity) and with materials other than timber.

The sensitivity of model simulations of the Hadley2CMSUL base scenario to timber demand assumptions is illustrated in Figure 6.21. The top line (indicated "inelastic demand") corresponds to the Hadley2CMSUL base scenario in the previous figure. Recall that a decline in demand growth or demand elasticity substantially lowers the rate of price increase for the region; the "elastic demand" scenario simulates an essentially fixed regional timber price throughout the region. Without a corresponding rise in timber prices, the combined effect of declining softwood productivity and

Figure 6.21. Sensitivity of Forestland Simulations to Regional Demand Assumptions: Hadley Base Scenario

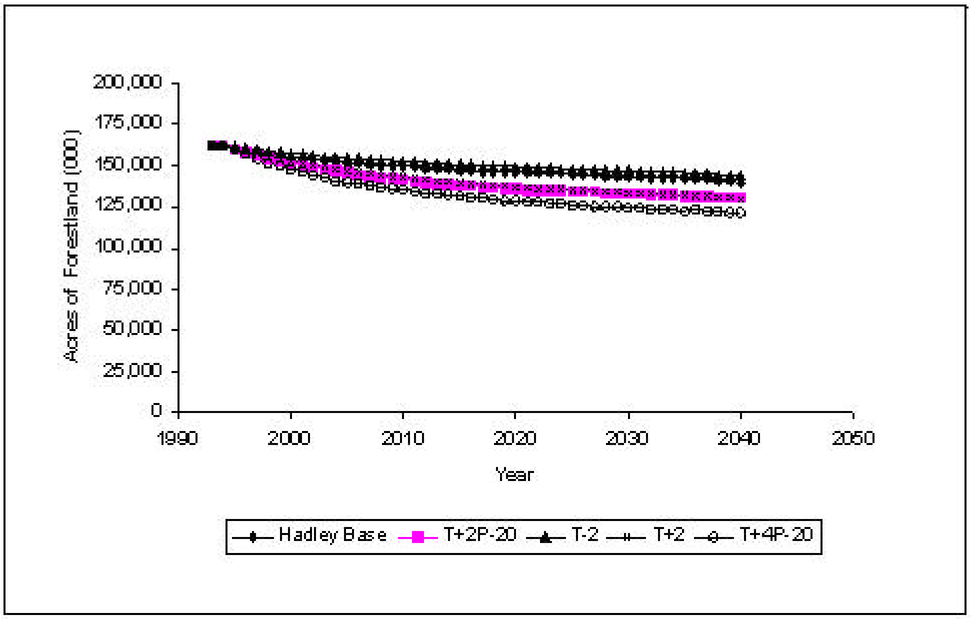


demographic pressures would generate a fairly steady decline in regional forestland by 2040 (over 20 million acres).

6.4.2.4 Sensitivity of Results to Variations in Climate Scenarios

Variations in the forestland simulations in response to different climate scenarios are illustrated in Figure 6.22. Because agricultural net income estimates are available only for the Hadley2CMSUL base runs, these simulations do not account for any climate-induced change in agricultural land returns. Therefore, they should not be interpreted as exact projections of forest areas under the different climate scenarios; rather, they collectively provide evidence of model sensitivity to this form of variation. The climate scenario indicating a 2ºC warming above the Hadley2CMSUL base indicates a moderate exacerbation of simulated forest area decline (10 million acres by 2040) due to the further

Figure 6-22. Sensitivity of Forestland Simulations to Different Climate Scenarios[a]



[a] Elastic dem and assumption, agricultural income effects not modeled

diminished forest productivity. The additional effect of a 20% decline in precipitation is undetectable due to forest compensation of reduced water use by increase water use efficiency from increasing atmospheric CO_2. The combined effect of Hadley2CMSUL + 4ºC and a 20% decline in precipitation leads to a more substantial simulated decline in forestland (up to an additional 20 million acres).

6.4.3 Summary of Land Use Findings

Although forests and agriculture dominate the southeastern US landscape, the effect of a changing climate on the relative productivity of these activities is just one of many factors that will determine how the region's land will be used in the 21st century. Urban and other developed uses, while currently a relatively small part of the regional land base, have expanded dramatically in the last two decades and are likely to continue to do so in the future. In recent years, much of the forest area converted to developed usement in the region was about equally offset by gains from forest establishment on previously agricultural land due to the decline in agricultural returns. This has tended to stabilize net forest area trends while exacerbating losses in agricultural land.

But relative changes in forest and agricultural returns potentially brought on by climate change could change the pattern of stable forest areas in the future if, as some scenarios suggest, agriculture can adapt to climate change in some parts of the region better than forests can. When the potential implications of climate change on land reallocation are analyzed under the Hadley2CMSUL base scenario, the model simulations suggest relatively little change in the way that land is allocated between forests and other uses between now and 2040. However, variations from the Hadley2CMSUL base (e.g., Hadley2CMSUL + 2 or 4ºC) could have more dramatic effects on land allocation. These more dramatic results should be evaluated with caution, however, as we have more limited information on the effects of climate change on economic returns to agriculture than on returns to forestry.

Chapter 7

Water Quality Assessment

7.1 Historical Perspective

The Southeast has abundant water resources, most of which are intensively managed. Most major river systems have been dammed and there are few minor streams that have not been affected by landscape alteration, channelization, surface or groundwater withdrawals, or other human activities. Based on over 50 years of streamflow records at 395 stations, Lins and Slack (1999) found that the Southeast showed a decrease in minimum daily discharge. Parts of Florida and Georgia appear to be experiencing a trend towards decreased minimum flows, while the lower Mississippi River Valley stations showed an increase in both annual median daily and annual minimum daily discharge (Lins and Slack, 1999). In Louisiana, precipitation simulated streamflow per unit drainage area has increased significantly since 1900 (Keim et al., 1995).

Although the Southeast is one of the wettest regions in the nation, water demand for domestic, industrial and agricultural uses is beginning to exceed the reliable supply (Ritschard and O'Brien, 1997). This phenomenon has already led to conflicts over water allocation and uses in some parts of the region. These conflicts can only become exacerbated as water quality issues are brought into the picture (Ritschard, et al., 1999). Current stresses on the water quality of the region include nonpoint source pollutants and nutrients, especially those associated with agricultural activities, water temperature problems associated with thermal cooling at power plants, saltwater intrusion in coastal and near-coastal areas and urbanization (Ritschard and O'Brien, 1997). As the population of the region continues to grow, competition for water between rural agricultural users and urban consumers is bound to increase, even in the absence of climate change. The losers in this conflict are likely to be the agricultural producers who may be asked to change their practices or leave the business. Changes in agricultural practices to maintain production with less water (such as increased fertilization) would then exacerbate water quality problems associated with nutrient loadings (Ritschard, et al., 1999).

Changes in climate that could result in decreased runoff during summer months generally reduce water quality in the Southeast (Mulholland et al., 1997). Summer low flows occur when water quality of many southeastern streams and rivers is at its lowest particularly associated with dissolved oxygen depletion (Meyer, 1992). Reduced dissolved oxygen during summer months can result in massive fish kills and harmful algal blooms in both coastal and inland waters.

Water quality issues beyond those associated with sea level rise or salt water intrusion are also a concern in nearshore marine environments. A large (8,000 to 18,000 square kilometers during 1985-1997) zone of oxygen-depleted (hypoxic) coastal waters is found in the north-central Gulf of Mexico and is influenced in its timing, duration and extent by Mississippi River discharge and nutrient flux (Justic et al., 1997; Rabalais et al., 1999). Nitrate delivered from the Mississippi Basin to the Gulf of Mexico, principally from non-point agricultural sources, is now about three times larger than it was 30 years ago as a result of increases in nutrient loading per unit discharge (Goolsby et al., 1999). Hypoxia, which is most prevalent in the lower water column, can adversely affect marine life and is a growing concern to those who harvest and manage Gulf fisheries. An increase in upper Mississippi Basin streamflow, where the majority of the nitrogen and phosphorus loading occurs, could lead to an increase in the hypoxic zone offshore.

7.2 Current Conditions Analyses

The water quality assessment focuses on the attainment of stream quality to EPA standards for dissolved oxygen (DO), nitrates (nitrogen) and pH for all major streams in the southeastern US. The EPA BASINS (Better Assessment Science Integrating Point and Nonpoint Sources; EPA, 1999a) software package, which operates within the ArcView GIS environment, was employed in the analysis. The BASINS system was used to query the EPA STOrage and RETrieval (STORET) database of water quality observations and geographically display the results. The database is indexed according the USGS Hydrologic Unit Code (HUC). The entire USGS database of water quality stream stations is also available and can be queried. BASINS allows the database to be queried directly or according to statistical characterization (*i.e.*, data quantiles or observations above threshold). Permitted effluent discharge data are also included by stream reach for each HUC. This method is outlined in more detail elsewhere (Cruise et al., 1999).

Current attainment status of each HUC was determined for each constituent using both mean observations and quantiles (15th and 85th) to characterize more extreme conditions corresponding to periods of intensive agricultural activities or dry weather. In areas where water quality degradation has been identified, correlations with the location and land use of the drainage basins via the BASINS data sets were performed. The effluent discharge data, in conjunction with the monthly runoff statistics for current conditions were also extracted where appropriate. These correlations were used to help determine the nature and origin of current stresses on water quality and to estimate future variability.

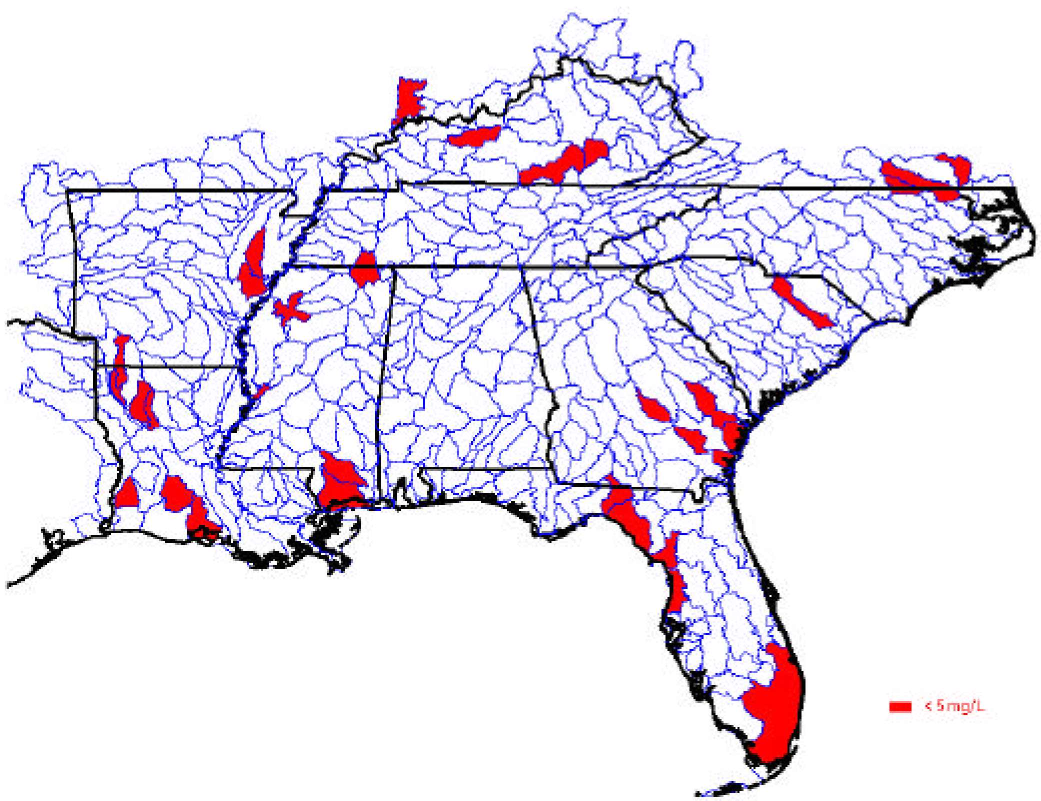
7.3 Results-Current Conditions

The results show that under current climates most HUCs in the Southeast do not experience attainment difficulties under normal conditions. However, in many cases water quality indices are either below or nearly below recommended levels. Stresses on the water quality of the Southeast appear to be associated with intense agricultural practices, coastal processes, and possibly mining activities. As might be expected, the impacts of these stresses appear more frequently during extreme conditions (85^{th} or 15^{th} quantile), probably associated with dry weather.

7.3.1 Dissolved Oxygen

Analysis of the current status (based on 1990-97 observations) of the watersheds in the Southeast for DO reveals few problems under mean conditions. However, it must be recognized that since the BASINS database is indexed to the major USGS hydrologic units, the analysis is based on a composite of observations on the larger streams in the region. These basins are generally of a size on the order of $10^3 – 10^4$ mi^2, thus, smaller tributaries may exhibit water quality degradation that will not be apparent at the spatial scale of this analysis. This study reveals only scattered HUCs in a few states that exhibit conditions below, or nearly below the recommended level of 5 mg/l during mean conditions. However, attainment problems under extreme conditions do arise at a few locations in most, if not all, states. Figure 7.1 shows the HUCs that exhibit DO values below 5 mg/l during at least 15% of the year. These periods may correspond to certain times during the year when practices associated with intense agricultural activity occur (e.g., discing, fertilizing, or flushing of fields) or merely dry weather conditions. Figure 7.1 also reveals that the basins that experience DO problems during these periods do not fall into any regular pattern throughout the region except that several are immediately contiguous to the Gulf Coast. This is not surprising in that coastal basins and estuaries frequently exhibit low DO levels. The extreme periods during which these levels occur along the gulf may correspond to periods of low fresh water inflows. Correlations with the land use database reveal that the non-coastal basins usually appear to be located in rural agricultural areas. Again, this may be a function of the fact that most of the sampling stations are located on fairly large watersheds and are more frequently in

Figure 7- 1. Dissolved Oxygen Extreme Conditions

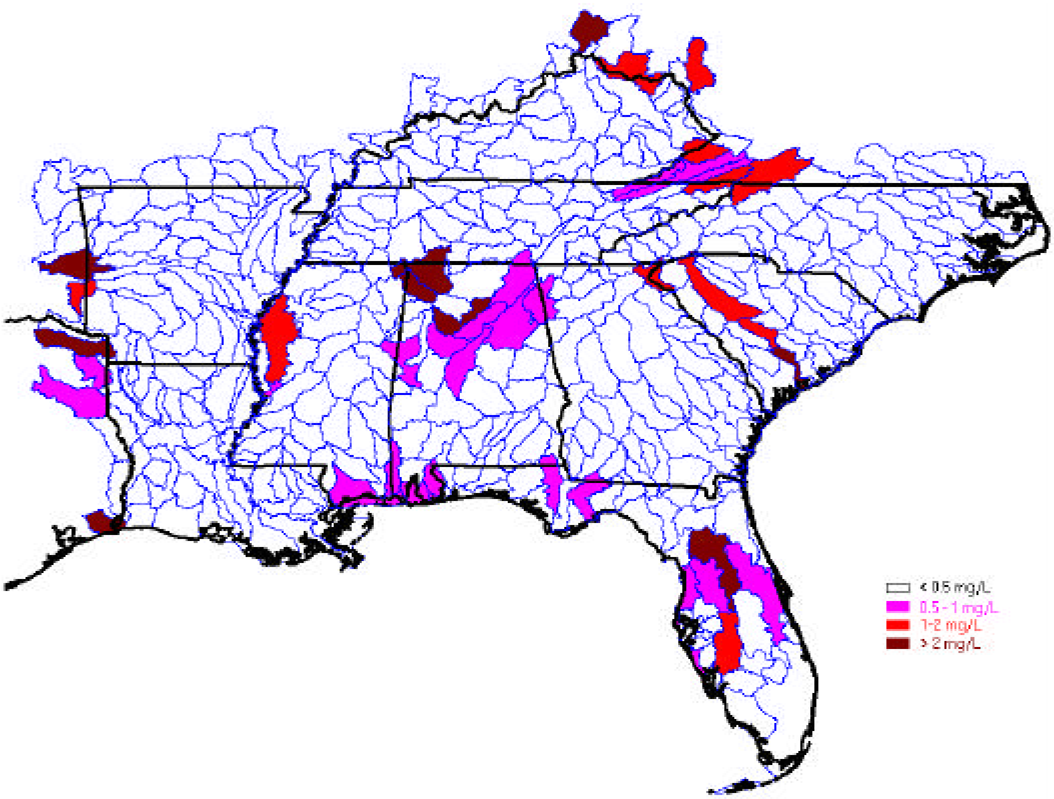


undeveloped areas than in urban environments. HUCs that exhibit low DO levels, either during mean conditions or extreme periods, were further analyzed under the future climate scenarios.

7.3.2 Nitrates

Nitrate levels of streams in the southeastern US were used as an indication of nutrient contents in these HUCs. Nitrate levels were used because they represent the index that appears to be most consistently reported over all watersheds. Observations of nitrate as nitrogen were present for nearly all streams in the region. Excessive levels of nutrients can result in harmful conditions such as algal blooms, which can reduce DO levels. The current status (1990-97) based on mean observations for total nitrate (nitrogen) content for streams of the southeastern US reveals that many of them exhibit levels above 0.5 mg/l NO_3-N and in some cases as high as 4-5 mg/l NO_3-N (Figure 7.2). This figure reveals that in the case of nitrate (nitrogen), there does appear to be a definite pattern of higher nitrogen in areas of intense agricultural activity and in proximity to the Gulf Coast. Large regions of higher nitrate levels are revealed in areas of high agricultural productivity such as the Warrior basin in Alabama, the Tombigbee basin on the Alabama/Mississippi border, portions of the Chattahoochee watershed in Georgia and Alabama and in central Florida. Coastal basins and estuaries in Louisiana, Mississippi, Alabama and Florida also reveal nitrate levels above 0.5 mg/l NO_3-N under mean flow conditions. As might be expected, extreme conditions appear to lead to much higher nitrate levels during at least 15% of the year with levels reaching 6-10 mg/l NO_3-N in some of the basins.

Figure 7- 2. Nitrate Nitrogen Mean Conditions



However, it is interesting to note that in most cases, these basins do not correspond to those that exhibit low DO levels. The scale of the analysis is also undoubtedly a factor in these results as only larger basins are represented. These streams generally exhibit fairly high flow rates and velocities and thus are capable of significant reaeration. It is highly likely that nitrogen/DO relationships do exist at smaller scales within these larger basins. The scale effects may also be obscuring any water quality degradation associated with urban development in the Southeast as well. As in the previous case, those HUCs that have revealed nitrate problems are being examined under streamflow conditions projected for the future climate scenarios.

7.3.3 pH

Analysis of pH levels in the streams of the region revealed that in cases where pH levels were outside the recommended range of 6.5-9.0, the deviation was on the higher side much more often than the reverse. Conversely, in only a few cases, did very acidic pH values (< 6) appear, even under extreme conditions. Again, this anomaly may be a function of the fact that only major hydrologic units are represented in the BASINS database.

The geology of the Southeastern region may also be somewhat responsible for the fact that the waters of the region rarely exhibit significant acidic characteristics. The underlying strata of much of the region (the piedmont, ridge and valley and the Appalachian highlands) is karst limestone. The runoff from this type of terrain usually exhibits high levels of alkalinity when compared to runoff from granite formations. The carbon in the limestone strata tends to neutralize any acidic content that may be associated with runoff.

7.4 Potential Impacts of Climate Change

7.4.1 Methods

7.4.1.1 Streamflow Modeling Under Future Climates

Using the Hadley climate model, two "windows" of future climate conditions were considered corresponding to the 2020-2039 and 2080-2099 time periods. For comparison purposes, precipitation and temperature conditions from these two 20-year "windows" were compared with the last twenty years of the observed data (1974-93). (Figures 7.3-

7.6) show the average monthly precipitation for the three 20-year periods plotted for several locations around the southeastern US. These figures show a distinct pattern of behavior by grid location with the northern and eastern most areas showing increased precipitation through most of the year for the 2020-39 period with the exception of early spring (March/April). During the 2080-99 period precipitation is expected to increase throughout the year in the northern latitudes of the region (Figs. 7.5 and 7.6). However, the picture is quite different for the southwestern portion of the region (Figs. 7.4). The model projects significantly decreased precipitation during most of the first half of the year during the 2020-39 period and somewhat decreased rainfall during most of the early

Figure 7- 3. Hadley Vemap Grid 5032: Central Florida

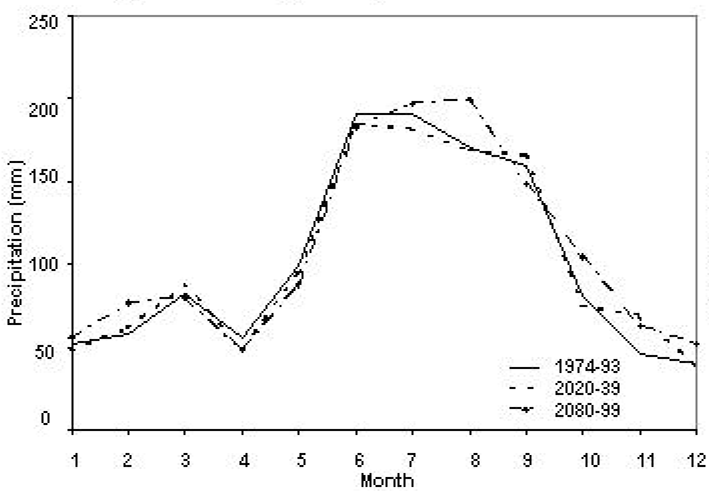


Figure 7- 4. Hadley Vemap Grid 4211: Mississippi Gulf Coast

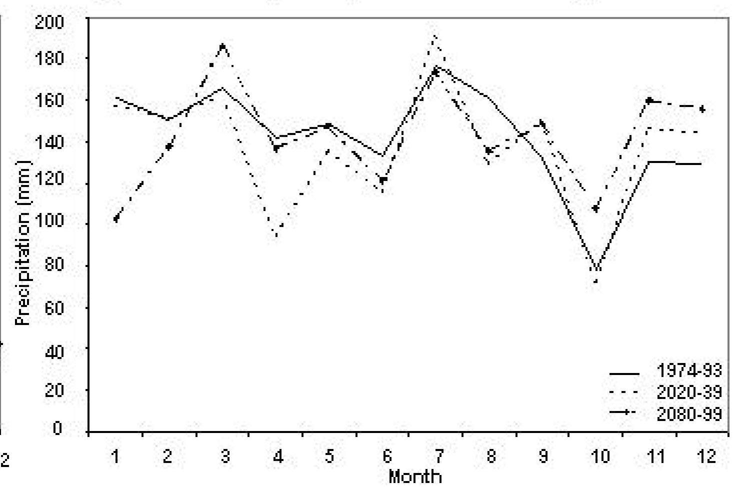


Figure 7- 5. Hadley Vemap Grid 3993: North Georgia

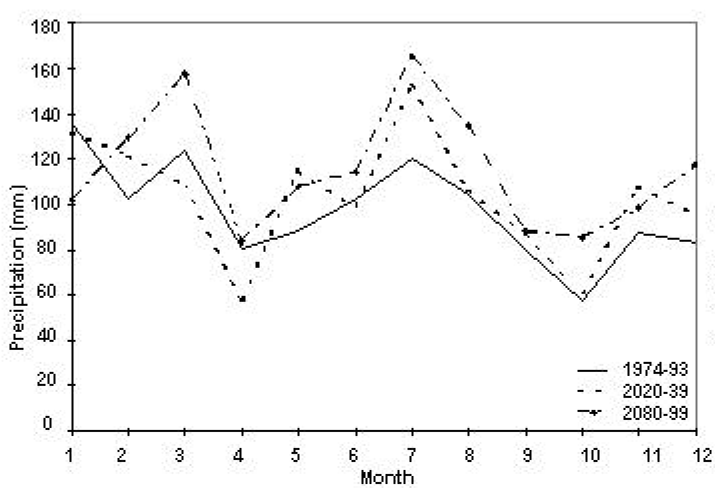
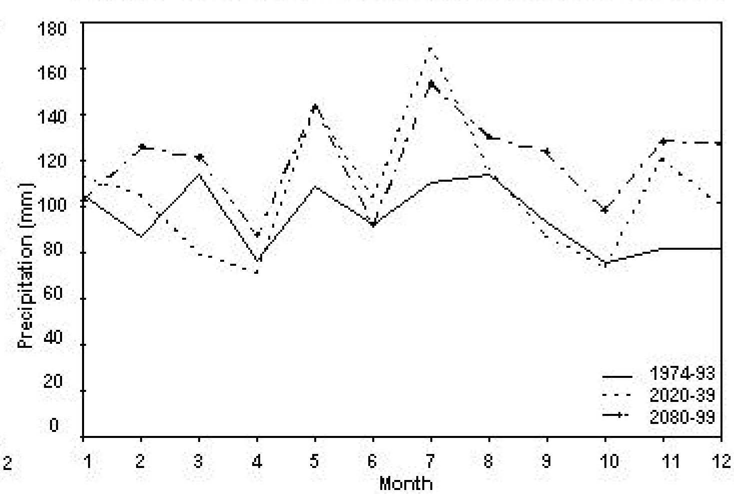


Figure 7- 6. Hadley Vemap Grid 3083: Coastal North Carolina



months during the 2080-99 period. For example, Ritschard, et al. (1999) show that, under the Hadley scenario, precipitation in the first six months of the year in southeastern Mississippi is projected to decrease by nearly ten percent in the 2020-2040 period. Only during the later months of the 2080-99 period does precipitation increase significantly for this region with only slight increases for some months projected for the 2020-39 "window". These results indicate that in the southwestern portion of the region water quality stresses could be significantly exacerbated during the first half of the next century for much of the year with some relief coming toward the later part of the century.

A key element in the determination of future surface water quality in the southeast will be the streamflow conditions that develop under future climates. In order to examine these conditions for the region as a whole, two methods of analysis are possible. In some regional studies (e.g., Fisher, *et al*., 2000), future streamflow conditions are obtained through detailed analysis of indicator watersheds in the region. Computer models are used to simulate the relevant physical processes (E.T., Soil Moisture, Runoff, etc.) using input climatological data from the GCM runs. A small number of basins are analyzed, each used to represent a set of physiographical conditions present in the region. The results of these studies are then considered representative of the region.

Another method would be to develop some technique to simulate conditions for the entire region. Of course, a physically based model executed at a course spatial grid would be the preferred approach for this task. However, such a model was not available to the investigators for this study. Instead, a hybrid system was developed that included a regional stochastic model supported by physically based modeling on a limited scale. This method was employed due to the limitations in time and resources available for the study. It was not possible to develop the necessary input data for physically based modeling for every HUC in the southeast for which modeling was necessary. In the first phase of the assessment, the hybrid stochastic model was used to examine the general trends in runoff over the region. In the next phase, beginning in late 2000 and extending through 2001, areas that were identified in the first phase as particularly susceptible to climate change will be intensively studied using a range of physically-based climate, hydrologic, agricultural and forestry models.

7.4.1.2 Development of the Stochastic Model

First, a simple regionalized stochastic streamflow model was constructed for each area of the Southeast where potential problems were identified. Observed streamflow in each area was normalized by removing the effects of scale (dividing by the mean value) as well as deterministic cycles and autocorrelation effects. The resulting normalized series from a few stream gauges located in a given geographical region were then averaged to obtain a regionalized distribution of errors. This procedure is analogous to the indexing procedure used in regional frequency analysis (Dalrymple, 1960). The normalized regional data set was then related to the normalized precipitation residuals for the region by regression. Attempts were made in several regions to include the normalized residuals of the temperature series into the analysis but in all cases it was found that the regression coefficient for temperature was not significant. The last 20 years of the observed record (1974-93) were used to gain the regression equations, which were then applied to the two future climate "windows" under consideration. Computed cross correlations between the two normalized series ranged from a low of about 0.4 (coastal North Carolina) to a high of about 0.75 (Mississippi) for various areas of the Southeast region.

These results, in conjunction with the 60% or more of the variance accounted for by the deterministic components (annual cycle and monthly autocorrelation effects), indicate that 75%-90% of the variance in monthly streamflow is accounted for by the method. However, the modeled processes are nonlinear and non-stationary so that the methodology is still subject to considerable unexplained error (in addition to the large error inherent in the predicted climate data). The regionalized equations were employed with forecasted precipitation from the Hadley model to predict monthly residuals for the two 20-year future "windows". Stochastic streamflow series were then reconstituted by merely adding back the deterministic components from the original observed streamflow series. Due to the simplifying assumptions on which it is based, the regional model is considered nothing more than a method for scaling the precipitation variability shown in Figures 7.3-7.6 into equivalent streamflow based on current rainfall-runoff relationships that exist for geographical regions of the southeastern US. It should be noted that these relationships were used on a qualitative basis only, *i.e.*, they were employed only to examine the general pattern of runoff variation over the southeast region during future periods and not to make any quantitative assessments.

7.4.1.3 Physically Based Modeling

The major weakness of the stochastic approach is the assumption of stationarity of variance. Of course, there is every reason to believe that this will not be the case.

Increases in temperature during the next century can be expected to alter the evapotranspiration characteristics of the region. Attempts to include normalized temperature anomalies into the stochastic model were unsuccessful. Therefore, it was clear that some physically based modeling that would include these factors was necessary in order to evaluate the general accuracy of the stochastic model. The physically-based SWAT (Soil Water Assessment Tool) model was used for this purpose. SWAT is a soil water balance model developed by the US Agricultural Research Service to examine the impacts of agricultural practices on runoff and water quality (Arnold and Allen, 1994; Srinivasan and Arnold, 1994; Rosenthal et al., 1995; Srinivasan et al., 1998) and is being used by the authors in several locations within the Southeast (Cruise et al., 1998, Limaye, et al., 2000). SWAT maintains a daily soil water balance on a watershed and includes surface runoff computed from the curve number technique and ET estimated by the Penman-Monteith method. Input requirements include soils characteristics, daily rainfall and temperature series, monthly solar radiation, land cover, vegetation leaf area index, and physical basin characteristics such as area and slope. The curve numbers are obtained from the soils and land cover data for a watershed and can vary throughout the year. Even though the model includes nutrient transport modules, it was employed only for runoff computations in the present analysis due to time and resource limitations as discussed previously.

SWAT modeling was accomplished in support of the stochastic approach in Georgia, Mississippi and Tennessee. It was felt that these simulations represented a sufficient breadth of coverage for the southeast region. The SWAT model was calibrated to observe streamflow data for the 1974-93 period and was used to simulate future streamflow series. The results from the SWAT simulations were then compared to those generated by the stochastic model previously discussed. For example, as shown in Figure 7.2, five HUCs within Mississippi exhibit nitrate nitrogen levels above threshold during mean flow conditions. SWAT was executed for each of the five HUCs where potential nitrogen problems were identified. These watersheds fall roughly into three regions of the eastern side of the state representing the north, middle and coastal zones. Therefore, the stochastic model could be developed for these three regions. Comparison of the results from the two approaches for the Mississippi Gulf Coast region (Figure 7.7) reveals that the SWAT model runoff simulations reflect the monthly variability of the Hadley precipitation estimates much better than do the stochastic model predictions. Not surprisingly, the stochastic model tends to smooth and damp the monthly variability evident in the precipitation estimates. Still, the overall seasonal pattern of streamflow simulations from the two models was similar in that they generally show increased runoff (above current) for the winter and early spring of the 2020-39 time period, followed by decreased runoff during the late spring/early summer period. They both show generally increased runoff through middle and late summer and decreased runoff again during the early fall season. The pattern is also similar for the 2080-99 period with runoff increasing or remaining the same for most of the year except for early winter and the month of April. These results were typical of those obtained from comparisons of the two modeling approaches. Analysis of these results led to the conclusion that the stochastic model is sufficiently accurate in its depiction of the general pattern of runoff that it can be employed in the qualitative manner in which it has been used for this study.

Figure 7.7 Comparison of Hydrologic Model Results for Mississippi Coast

7.4.2 Results of Future Runoff Simulations

The predicted spatial and temporal patterns of streamflow were used to reevaluate those HUCs that demonstrate current water quality problems, or those that might actually improve under future climates. The analysis was performed for wet (spring) and dry (late summer or fall) seasons. The estimated average monthly streamflows were used to predict whether streamflow conditions would improve or decline during each season for each of the regions for which the analysis is performed. Future streamflow projections (in terms of increased or decreased runoff by season) were used to broadly determine where hydrologic conditions may improve or worsen. Even in areas where streamflow is projected to increase, the increased runoff could result in further degradation of water quality by increasing constituent loading to the streams. The BASINS software includes the permitted effluent discharge data by stream reach for each HUC and a database is under construction to contain future population projections and land use changes at the county level for the 2000-2100 time period. These data can be used in conjunction with the results of the present study to examine future water quality conditions in greater detail during any future assessment.

The results of the future streamflow simulations using the stochastic approach (with support from the SWAT model) are shown for the entire Southeast region for wet and dry seasons in Figures 7.8-7.11.

Figure 7-8. Future Streamflow Conditions
2030 Dry Season

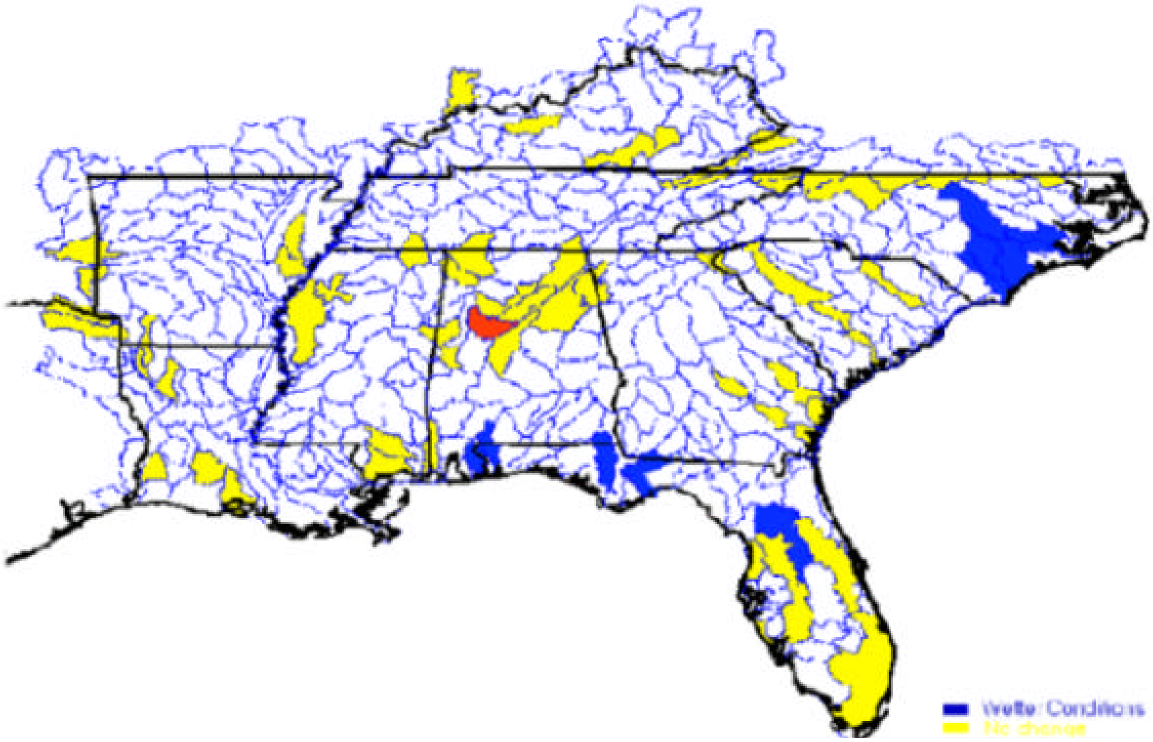


Figure 7-9. Future Streamflow Conditions
2030 Wet Season

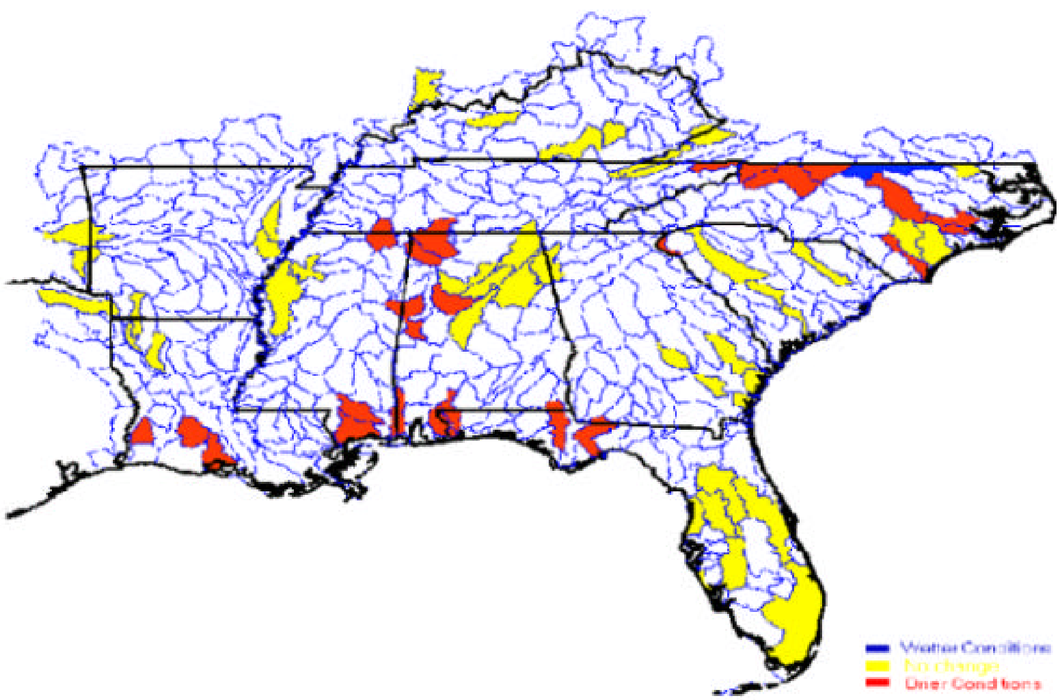


Figure 7-10. Future Streamflow Conditions
2090 Dry Season

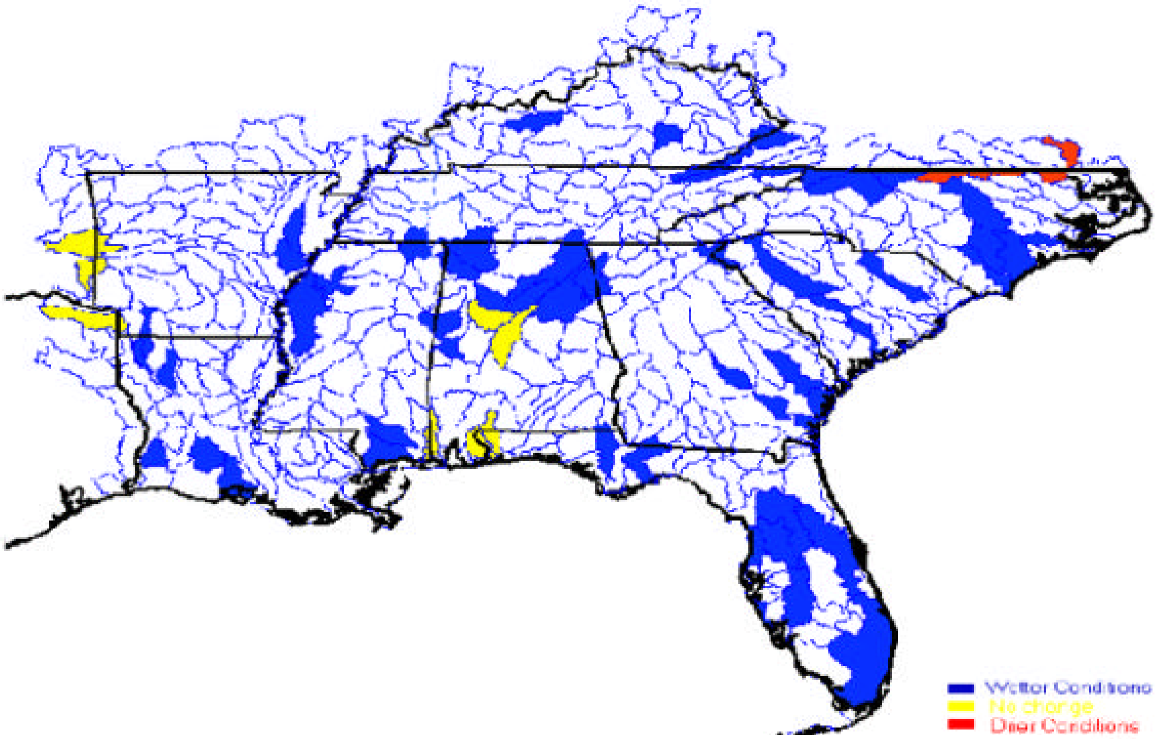
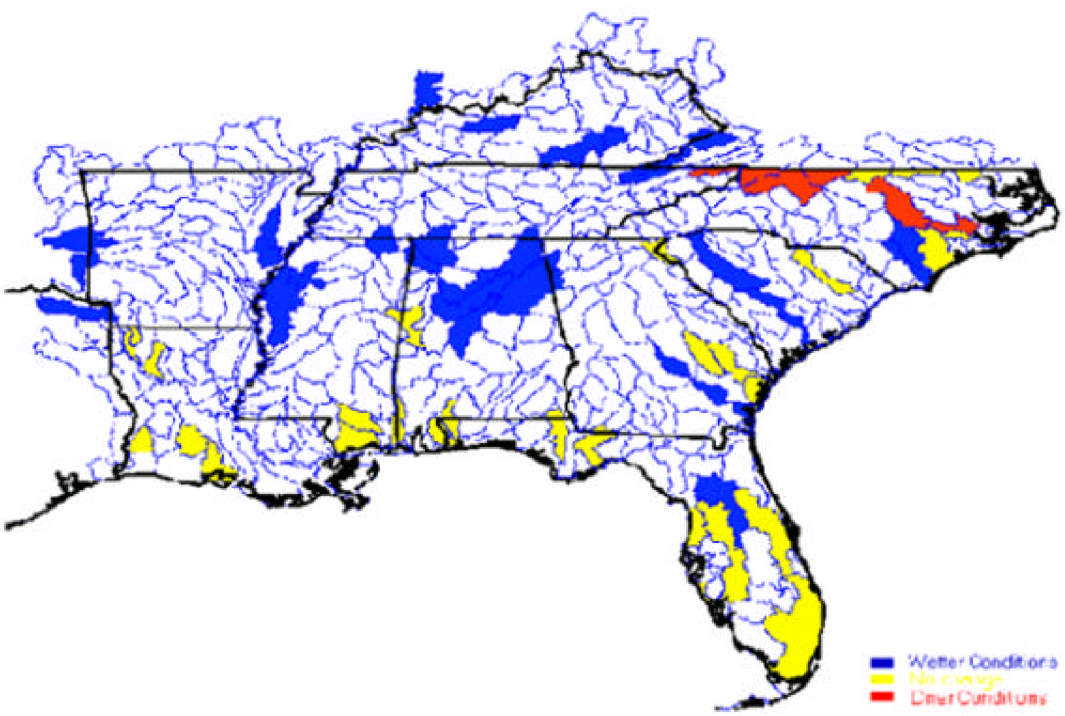


Figure 7-11. Future Streamflow Conditions
2090 Wet Season



7.4.3 Possible Consequences for Water Quality

It is possible to discuss the potential impacts of future climate change on the water quality of the Southeastern United States by examination of seasonal pollutant loading and water quality as climate related factors. There exists quite a bit of literature on this subject. It is generally agreed that the relationship between nonpoint source pollutant loading, precipitation and runoff is a positive one, *i.e.*, increased precipitation and runoff results in increased pollutant loadings (Barbe', *et al.*, 1996; Alexander, *et al.*, 1996; Meals and Budd, 1998; Choi and Blood, 1999). This rule certainly applies to the nutrients examined in this study (Barbe', et al., 1996; Alexander, *et al.*, 1996, Fisher, *et al.*, 2000). Figure 7.8 shows that dry season runoff and streamflow are expected to remain about as in the present over the next 30 years for most of the region, with the exception of coastal regions in Louisiana, Florida and North Carolina. Thus, one would expect increased nutrient loading in these coastal areas during the summer/early fall of this period. Conversely, Figure 7.9 shows that wet season conditions are expected to be significantly drier over most of the region in the 2030 period, thus potentially leading to reduced nutrient loadings during the winter/spring season. Therefore, a scenario seems to be set up for the next 30 years in which the winter/spring season of each year will see reduced streamflow and nutrient loads to be followed by increases in flow and nutrients later in the year, particularly with respect to coastal streams and estuaries. Of course, the land use adaptation policies to be adopted by the land owners during this period will also play a significant role in the level of nutrient fluxes to the water bodies. However, assuming fertilization begins sometime in the spring of the year, the drier conditions during this period may reduce the initial rate of washoff of nitrogen from agricultural and residential areas. However, this phenomenon may be countered by increases in fluxes of both nitrogen and phosphorus during the summer and early fall. Since this is the period during which crops are harvested, the resulting water quality stresses could be exacerbated due to additional pollutant carriers such a sediment and other solids associated with harvesting activities.

As for longer term predictions, Figures 7.10 and 7.11 show that streamflow is expected to increase over most of the region for the 2090 time frame, both in wet and dry seasons. There are some exceptions to this rule, particularly for the wet season runoff in several North Carolina basins where flow is predicted to decrease and in Florida and the Gulf Coast where it is forecast to remain as current. These results would appear to indicate that nutrient loading would tend to increase in most of the region during this time, with the exceptions noted above for North Carolina where decreases in wet season loads would be expected and in Florida and the coast where conditions would remain the same.

The potential impacts of climate change on the dissolved oxygen levels of the region can be analyzed in a similar manner. However, in this case, the water temperature also plays an important role in the DO mechanics. The relationship between DO and temperature is well established through the application of Henry’s Law (Tchobanoglous and Schroeder, 1987). In general, the warmer the temperature, the less oxygen the water can hold. The general positive relationship between air temperature and stream temperatures has also been well established (Johnson, 1971; Stefan and Preud'homme, 1993; Mohseni, *et al.*, 1999). Thus, one may expect warmer water temperatures in the southeast over the next 100 years. However, the effect of this trend on water quality may be somewhat countered during much of the future by increases in precipitation and streamflow. Increased streamflow would be expected to perhaps develop increased channel velocities and thus afford greater reaeration capacity of the streams than do current conditions. Based on these factors, it is difficult to predict how future dissolved oxygen levels may react to changing climate conditions. However, the situation is a little more clear in the case of the 2030 wet season dynamics. As shown in Figure 7.9, streamflow is expected to decrease over much of the region during this period, particularly in coastal areas. This phenomenon, along with increased temperatures may exacerbate any DO problems that may exist in these areas due to the already low summer streamflows (Mulholland, et al., 1997).

The above analyses appear to indicate that the most vulnerable areas of the Southeastern Region with respect to future climate-related water quality degradation are those water bodies in close proximity to the coast. While this is particularly true of the Gulf Coast region, it is also apparent to a lesser extent for the Atlantic Seaboard. Increased nutrient loads for certain parts of the year, together with decreased streamflow for the following periods along with increased temperatures may well lead to further degradation of water quality in these streams and estuaries.

7.5 Summary of Water Quality Findings

Three water quality indices were examined in this assessment, which represent the three indices that are generally published in EPA literature for the nation as a whole and are considered as the more important measures of ecosystem health. In terms of the current stresses on water quality in the Southeast, the conclusions from this study are that, while water quality problems across the southeastern US are not critical under current conditions, attainment status is not met in several basins during the majority of the year, and can become critical under extreme conditions during some portions of the year. Interesting results include the observation that streams which currently exhibit low DO levels do not correspond to those basins where nutrient levels appear high. However, in both cases, the problems appear to be related to agricultural practices. In addition, coastal or near coastal streams sometimes exhibit non-attainment status in both DO and nitrate levels. Results do not reveal significant water quality degradation associated with urban development at the scale of this analysis, however, we are not prepared to rule out such development as a water quality stressor.

Climate scenarios based on the results from the Hadley model reveal contrasting results in terms of temperature and precipitation estimates over the region, so that in some cases conditions may improve while in others they may degrade. However, increases or decreases in gross precipitation did not always scale into significant changes in streamflow as predicted by the stochastic model. With this caveat in mind, the results do appear to indicate that the Gulf Coast area may be particularly vulnerable to degraded conditions during the first half of the next century. The model predicts increases in rainfall and streamflow for certain portions of the year in the region for the 2020-39 time frame followed by decreases in streamflow for the rest of the year. Following literature results, one would then expect increased pollutant loadings followed by decreased streamflow and assimilation capacity. Intense agricultural activity including discing and planting in the early spring, fertilizer application in the late spring/early summer and harvesting in the fall may significantly exacerbate water quality conditions during this period. Other studies (Mulholland, et al., 1997) have indicated that reduced streamflow in summer tends to lead to degraded water quality conditions in the southeast, perhaps associated with higher summer temperatures. Elsewhere, the results appear to indicate that streamflow conditions will remain about the same as in the present for most of the Southeast during both spring and fall seasons for the 2020-39 time frame.

The simulations for the 2080-99 period reveal that some relief may come for the Gulf Coast region, particularly during the dry summer/fall season. In fact, the results show that nearly the entire Southeast region will exhibit increased streamflows during this period. In contrast, conditions along the Gulf Coast and the eastern seaboard are expected to remain about the same as present during the spring wet season, while streamflow is predicted to increase in the north central and western portions of the region. Of course, these increases in runoff may well lead to increased nutrient loads to these streams, particularly if fertilization rates have been increased in response to the earlier drier weather. Therefore, it is by no means certain that increased streamflow during the later stages of the century would necessarily lead to better water quality conditions, and in fact, the reverse may well be true.

Review of the results also reveals two more interesting observations with respect to impacts of future climate changes. First, a number of the basins that exhibit current problems are located along the Gulf Coast where they will be significantly impacted by sea level rise during the next century as well as the decrease in fresh water inflow predicted by the Hadley model. If the model projections are correct, these basins and estuaries in Louisiana, Mississippi, Alabama and Florida should see significant increases in salinity levels associated with salt-water intrusion as well as a degraded quality of the inflows that do occur. Based on these observations it is quite possible that many of these areas could exhibit eutrophic conditions throughout much of the year. Of course, these conditions would have a negative impact on the aquaculture and tourism industries in the region.

The second observation reveals that many of the basins currently demonstrating high nitrogen levels form the boundary between two states. The Chattahoochee boundary between Georgia and Alabama and the Tombigbee boundary between portions of Alabama and Mississippi are two outstanding examples. The results indicate decreased water availability throughout much of this region over the next 50 years. As streamflow and soil moisture decrease, the intensity of fertilizer application may increase and irrigation needs may become critical in certain southeastern locations (Ritschard et al., 1999). These issues could very well lead to intense competition for scarce water resources and conflicts between states over runoff treatment, storage, and control. A framework currently exists for resolving disputes between the states comprising the Appalachicola-Chattahoochee-Flint basin and a similar framework may need to be formed for the Tombigbee and other basins in the region.

7.6 Limitations on Water Quality Results

The water quality assessment analyses given in this chapter indicates generally where problems may arise over the course of the next century. However, it should be remembered that the results and discussions given above are based on a combination of atmospheric and hydrologic models along with assumptions and judgements of the investigators. The modeling results, particularly over the long time periods projected in this assessment, are subject to considerable error. Likewise, the assumptions and judgements employed in the application of the models and the analysis of the results may be open to differing interpretations.

Chapter 8

Air Quality Assessment

8 .1 Historical Perspective

Any change in daily meteorological variables associated with climate change in the Southeast could alter ground-level ozone formation in urban regions. Ozone in cities is the result of chemical reactions involving oxygen, nitrogen oxides (NO_x), volatile organic compounds (VOC) from incomplete combustion and natural biogenic emissions, and ultraviolet radiation. Previous studies have shown a large sensitivity of daily ozone to temperature with higher temperatures being nonlinearly related to higher ozone levels. Ozone concentration appears to show no dependence on temperature below 39-44°C (70-80°F), but they become strongly dependent on temperature above 50°C (90°F). One study suggested that a 4°C (7.2°F) temperature increase would lead to a 10% increase in peak ozone concentration (Smith and Tirpak, 1989). Another source attributes a 10% increase in smog events to each 5°C (9°F) increase in temperature (Akbari et al., 1992). While these statistical studies have linked temperature and ozone, the relationship is not all causal and the temperature relationship is perhaps largely reflecting other indirect relationships.

Temperature can directly affect the chemical kinetic rate coefficients although this effect is relatively modest. In terms of process sensitivity the largest impact is in the area of the thermal decomposition of organic nitrogen species which can then free up reactive nitrogen to continue photochemical production (Sillman and Samson, 1995). However, temperature may be a surrogate for other factors impacting ozone production. At higher temperatures absolute humidity is generally higher which can increase the efficiency of radical generation. Higher temperatures can also be associated with clear skies increasing the direct photolysis rates driving the photochemistry. Additionally, high temperatures in the summer are associated with light winds decreasing the dilution of precursors and directly increasing concentrations.

Probably the greatest indirect effect of temperature is in its impact on emissions. Biogenic emissions of reactive volatile organics such as isoprene are almost exponential with increasing temperature (Tinghey et al. 1981). Anthropogenic evaporative emissions from automobiles and fuel handling are also highly dependent upon temperature through vapor pressure relationships. In the Southeast higher temperatures also increase electricity demand for air conditioning, thereby increasing nitrogen emissions into the air through fuel burning electrical generation.

Thus, while the following analysis dwells on temperature it should be recognized that temperature may be simply a surrogate variable for these other processes and direct causality is not always to be inferred. Further, other processes such as dry deposition losses of ozone and nitrogen precursors may also have a large meteorological sensitivity and are not dealt well herein. This analysis is then as really more a study of the sensitivity of ozone to a well-defined climate variable – temperature than a complete assessment.

Trends in the level of ground-level ozone pollution have been obscured in the Southeast by short-term changes in meteorological conditions and by long-term changes in the level of fossil fuel combustion and evaporative emissions. Several authors have studied the effects of meteorological fluctuations on daily and annual ozone concentrations (Clark and Karl, 1982; Cox and Chu, 1993; McNider et al., 1995; Sillman and Samson, 1995; Flaum et al. 1996). Clear relationships between temperature and maximum ozone levels have been established in the Southeast (McNider et al., 1995; Sillman and Samson, 1995; Southern Oxidant Study, 1995), however the underlying processes leading to these relationships are still not clear. Fiore et al. (1998) comparing long-term summer ozone concentrations and daily temperature data across the U.S. found that no region experience significant increase in ground-level ozone concentration for the 1980-1995 time period. Martin (1998), on the other hand, studying meteorologically-adjusted ozone trends for 12 southeastern cities from 1981-1993 indicated that ozone levels have improved in four cities, worsened in three cities, and demonstrated no changes in the remaining cities. These studies underscore the difficulty in assessing the effectiveness of regulatory controls for ozone because of the influence of meteorological fluctuations on ambient ozone concentrations.

8.2 Potential Impacts of Climate Change

Not as much attention has been given to air pollution concerns in climate change studies as to the impacts in agriculture or water resources management even though air pollution levels, especially the concentration of ground-level ozone are dependent on meteorological conditions. For example, decreases in wind speed and mixing heights and increases in air temperatures in an urban area associated with climate change can increase air pollution levels masking or reversing the effects of emission reductions. These changes can then cause a violation of ambient air standards triggering substantial control costs that can easily exceed several hundred million dollars for a medium size urban area.

Because analytical tools and data needed to fully examine the air quality and climate relationships are currently lacking, a preliminary assessment was conducted that focused on the effects of climate variability and change especially related to variations in temperature on ground-level ozone production. Ozone is perhaps the most significant air pollution problem in the Southeast. Sunlight coupled with a large biogenic source of volatile organic compounds has made the South vulnerable to increasing levels as population has increased. Many areas in the Southeast marginally meet the National Ambient Air Quality Standard for ozone (120 ppb/1 hour-standard; 80 ppb/8-hour standard). Any increase in ozone levels could substantially increase of the number of cities and areas having to adopt costly control measures.

The assessment approach used a statistical regression model that considered the relationships among temperature, precipitation, and relative humidity and measured ozone concentrations on extreme days for four southeastern cities: Atlanta, Birmingham, Memphis, and Nashville (Myers, 2000). These cities were chosen because they are classified as either a non-attainment area or are close to being in non-attainment for EPA's ozone standard. The regression model was coupled with climate scenarios for 2030 and 2090, to estimate changes in ozone production for the four study sites. These estimated changes were then compared to 1995 base values, which represented measured ozone concentrations from selected sites within each urban area.

8.2.1 Methods

The multiple linear regression model used in this analysis was composed of several meteorological variables (maximum and minimum temperature, relative humidity, precipitation) and the previous day's maximum ozone values. The model was formulated as follows:

$$C_{new} = k_1C_{old}+k_2R+k_3H+k_4V+k_5P+k_6M+k_7N+k_8$$

Where: C_{new} = Tomorrow's maximum one hour average ozone concentration (ppb)
C_{old} = Today's maximum one hour average ozone concentration (ppb)
R = Today's average solar radiation ($kJm^{-2}d^{-1}$)
H = Today's average relative humidity (%)
V = Today's average vapor pressure (Pa)
P = Today's precipitation (mm)
M = Today's maximum surface temperature (°C)
N = Today's minimum surface temperature (°C)
$K_{1....8}$ = site specific numerical coefficients

The meteorological data selected were chosen primarily because they were available from the Hadley Center model output. The model does not include the effects of transport, atmospheric pressure, wind speed, or total sky cover because those data were not available from the GCM runs. The baseline historic meteorological data, which were obtained from the National Climatic Data Center, were run for three months (June, July, and August) in 1995 for verification purposes. All monitored ozone data (maximum hourly ozone concentration for each 24-hour period) for 1995 were obtained from EPA's Aerometric Information Retrieval System (AIRS) database. One station in Atlanta, five stations in Birmingham, two stations in Nashville, and two stations in Memphis were represented with their own regression model.

8.2.2 Results

Initially, the regression model results for 1995 (base year) were compared to the observed maximum ozone concentrations to determine how well the model could represent monitored data. As shown in (Table 8.1), the model over-predicted maximum daily ozone concentrations in 8 of the 10 stations. In all but one case, this overprediction ranged from 2-12%. However, the predicted value at the Atlanta site was 25% above the observed data. At the two Memphis locations, the maximum ozone concentrations were under-predicted by 9-12%. The amount of variation occurring in these regression models was also determined. The coefficient of determination (r^2) ranged from 0.41 at one of the Memphis sites to 0.63 at one of the Birmingham locations.

In general, the models were capable of explaining over 50% of the variance based on meteorology alone. It should be noted that this modeling approach did not consider emissions from biogenic or anthropogenic sources, which are likely to change over time with increases in urban population, transport of ozone or ozone precursors (e.g., nitrogen oxides) from outside the study areas, or other important meteorological variables such as boundary layer height, or wind speed and direction. The incorporation of some of these factors could certainly improve the regression model's performance, but doing so was beyond the scope of this preliminary assessment.

Table 8.1 Comparison Results (maximum ozone concentration, ppb)

Location	1995 Observed	1995Predicted	% Deviation
Atlanta			
Fulton	92	115	+25
Birmingham			
Fairfield	101	104	+3
McAdory	92	103	+12
Hoover	96	106	+10
Pinson	84	86	+2
Tarrant	83	92	+11
Nashville			
Percy Priest	90	97	+8
Trinity Lane	85	87	+2
Memphis			
Edmond	102	93	-9
Frayser	113	100	-12

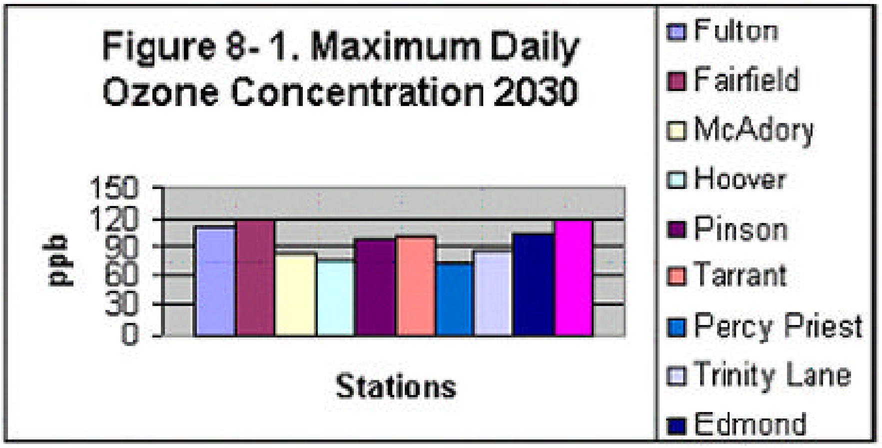
The regression model was next used to evaluate the potential impacts of changes in temperature and precipitation as predicted by the Hadley climate scenario for 2030 and 2090 and compared to the 1995 baseline. Since the model contains the previous day's maximum ozone concentration as a predictor variable, this value must be supplied for the first day of summer for each future year under analysis. In this study, initial values representing low (60 ppb), medium (80 ppb) and high (100 ppb) were used in a sensitivity analysis approach. In each case, the values were entered for June 1 of the year and the model was run for the June, July and August summer period. The results indicated that the maximum summer ozone values were not very sensitive to the initial value used in the analysis (Table 8.2). As shown in the Table, there was not a significant difference in the maximum value predicted by the model between the 60 ppb initial value and the 100 ppb initial value. For comparison with present baseline conditions, two

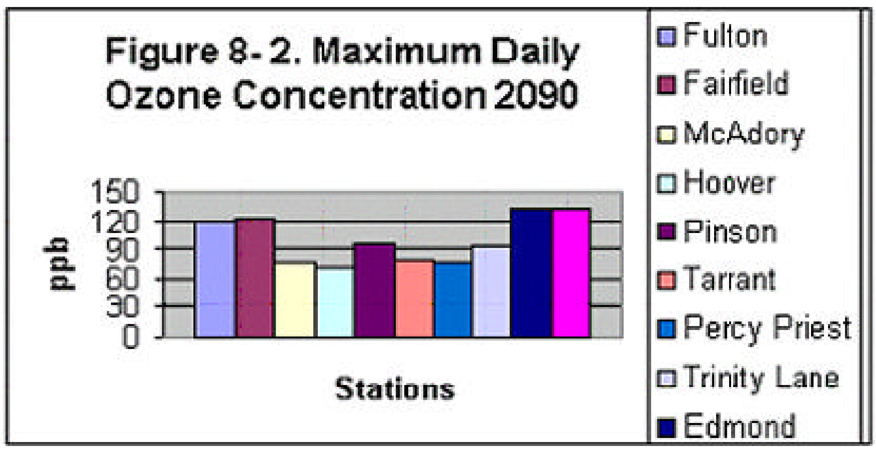
Table 8.2 Sensitivity of Maximum Daily Ozone to Initial Concentration at Ten Urban Sites in the Southeastern United States

Station	Initial Concentration (*ppb*)							
	60	80	100	Avg	60	80	100	Avg
	2030 Predictions				**2099 Predictions**			
Atlanta	0.93	0.94	0.94	0.94	1.06	1.06	1.06	1.06
Fairfield	1.40	1.36	1.22	1.33	0.99	0.97	0.89	0.95
McAdory	0.75	0.82	0.93	0.83	1.27	1.27	1.28	1.27
Hoover	0.56	0.62	0.74	0.64	1.19	1.19	1.18	1.19
Pinson	1.27	1.27	1.23	1.26	0.85	0.88	0.94	0.89
Tarrant	1.25	1.24	1.12	1.20	0.99	0.99	0.94	0.97
Percy Priest	0.56	0.63	0.75	0.65	0.89	0.89	0.89	0.89
Trinity	0.99	0.99	0.99	0.99	0.89	0.89	0.95	0.91
Edmond	1.29	1.29	1.22	1.27	1.35	1.35	1.28	1.33
Frayser	1.29	1.29	1.29	1.29	0.80	0.80	0.80	0.80

extreme ozone days based on the 1995 data were chosen for each station and used throughout the analysis.

The future climate data used in the regression model were taken from each grid cell (0.5º or ~40 km apart) within the urban area. The results are presented on a site-by-site basis to illustrate the variability found among the stations. As shown in (Fig. 8.1), maximum daily ozone concentrations increased in 2030 at half of the study sites. In only two cases, Birmingham (Fairfield) and Memphis (Frayser) did the maximum daily ozone concentrations approach the air quality standard of 120 ppb. By 2090, the Atlanta station (Fulton) in addition to those in Birmingham (Fairfield) and Memphis (Edmond and Frayser) either approached or exceeded the maximum daily ozone standard (Fig. 8.2). The largest increases were found at the two stations in Memphis. Since the average mean





error for all stations was 14.9 ppb (range = 13.0-18.1 ppb), these predicted values may be slightly higher or slightly lower than those estimated by the model. The results suggest that considering only changes in meteorological conditions (i.e., especially temperature) maximum daily ozone standards may be reached or exceeded at stations within these three southeastern cities. (The concept of an actual technical violation under current EPA regulations depends on the number of exceedances of the 120 ppb one hour level over a three year period. Thus we are only using the 120 ppb as measure of the violation potential. In recent years, Atlanta has been designated as a serious ozone non-attainment area and Birmingham as a marginal ozone non-attainment area (EPA, 1999b). Thus a first order examination of the impact increases in temperature in the future would appear to only exacerbate these current conditions. Furthermore, the effects of increased emissions during this time period because of increased use of combustible fuels were not considered nor were the effects of increased temperature on isoprenes and other biogenic emissions except as reflected in the temperature dependent ozone statistics..

The Hadley climate model represents about a 1ºC increase in maximum temperature in 2030 and 2ºC increase by 2090. To evaluate the potential impacts of a broader temperature range suggested by other climate models (e.g., Canadian Centre model), a series of sensitivities were performed assuming 3ºC, 4ºC, and 5ºC increases by the end of the next century. Surprisingly, no additional stations showed maximum daily ozone concentrations approaching the ozone standard of 120 ppb at these higher temperatures. At the unrealistic future temperature rise of +5ºC, one station in Nashville reached a maximum ozone concentration of 115 ppb. At the higher temperatures, the four stations that had exceeded the daily ozone standard under the Hadley climate scenario, showed increases in maximum daily ozone concentration of about 3-5% per degree increase.

8.3 Summary of Air Quality Findings

Although the air quality assessment is very preliminary because of the nature of the regression model used, it does suggest that future increases in temperature could adversely affect several urban areas within the Southeast. This is especially true in the case of cities like Atlanta and Birmingham that are already faced with air quality problems related to ground-level ozone. The situation may be even worse in these two cities than shown in our results. For example, Pollock et al. (1988) has observed that high ozone concentrations are consistently under-predicted by regression equations. These authors attribute this to the least-squares fitting procedure, which is designed to limit the overall mean square error. Because high ozone levels (100 ppb or more) are generally extreme values and occur only rarely, they might not be important in determining the regression coefficients according to Pollock et al. (1988).

. Because of the current difficulty in assessing the influence of meteorological fluctuations on ambient ozone concentrations, it is equally difficult to assess the potential effects of future climate change urban air quality. An understanding of air quality/meteorological relationships is not only key to understanding the impact of climate change but also in interpreting air quality trends. Meteorological variability can mask trends in air quality due to control strategies affecting emissions thus causing one to abandon control strategies too soon or stick with inefficient control strategies.

In climate change assessments, air quality relationships may be much more complicated than the simple picture presented here where only direct meteorological variables such as temperature and wind speed are considered. The budget of ozone and other air quality constituents are often controlled as much by losses as production. If in future climate states substantial variation in precipitation were to occur, reduction in plant productivity which directly affects ozone uptake in the stomata could alter the ozone budget. Also, changes in landscape affecting albedoes or uv radiative paths in the atmosphere could alter photolysis rates affecting ozone. Such macroscale indirect effects were not incorporated in the current analysis. The pursuit of more complete approaches to understand these complex relationships seems worthwhile and important to any future assessments of potential air quality changes and in determining trends in air quality. The reader should also refer to the air quality assessment under the Climate Change Impacts under the U.S. Global Change Research Program and to air quality trends developed by the U.S. Environmental Protection Agency and the multi-agency North American Ozone Strategy on Tropospheric Ozone (NARSTO) program.

Chapter 9

Extreme Weather Events

9.1 Historical Perspective

Reliable records exist for North Atlantic hurricane activity since 1944 and for those making landfall in the United States since 1899 (Landsea, 2000). The record shows that there has been substantial annual and decadal variability in Atlantic hurricane activity over the period of record. The first two decades of the century was a period of relative quiet in terms of landfalling hurricanes in the Atlantic which was then followed by a long period of much higher activity streaching from the mid 1920's through the 1960's. During this period, the decades from the 1940's through the mid 1960's constituted the period of greatest activity (Landsea, 2000). This period saw an average of almost one intense hurricane a year make landfall somewhere on the US Atlantic coast compared to the overall average of around 0.34 per year. In contrast, the more recent period of the 1970's through the mid 1990's have again seen a decrease in hurricane activity similar to the first two decades of the century.

The Gulf Coast region of the US has exhibited somewhat less long term variability in hurricane activity and strikes than has the North Atlantic as a whole (Landsea, 2000). The long term average number of hurricanes to make landfall in this region is about 0.35 per year, while the 5-year moving average varies from 1.5 per year to zero. The maximum number of hurricanes to hit this coast line in any year over the period of observed record is two.

However, during the past 30 years, the Gulf of Mexico has seen a decrease in the number of hurricanes making landfall. Hurricanes Andrew, Hugo, and Brett are the only

Category 4 storms to make landfall since 1969. But since 1900, 35% of all hurricanes hit Florida and along the middle Gulf Coast, 50% or more of all hurricanes making landfall are Category 3 or higher (Heinz Center, 1999). Property losses due to hurricanes increased from less than $5 billion per decade between 1900 and 1940 to about $15 billion per decade during the 1960s to 1980s, however, the number of deaths attributed to hurricanes has declined dramatically since the 1950s (Pielke and Pielke, 1997).

Significantly, the variation in Atlantic hurricane activity over the past 100 years has been shown to be related to variations in the Atlantic sea surface temperature (SST) structure (Gray, 1990; Gray, *et al*., 1997). According to Landsea (2000), "Warmer (cooler) than average conditions in the Atlantic north of the equator coupled with cooler (warmer) than average SST's in the South Atlantic favor increased (decreased) intense hurricane activity". Conditions in the Atlantic, which have their obvious correlaries in the Pacific basin associated with ENSO activity, are obviously subject to regional climate change impacts, and thus may significantly impact extreme weather activity in the Southeastern US under future climate scenarios.

Extreme climate events in the U.S. over the past 20 years have resulted in 40 weather-related disasters with damages/costs from individual events in excess of $1 billion; 23 of these disasters occurred in the southeastern states with total damages/costs of about $88 billion (Table 9.1). Most of the property damages were associated with floods and hurricanes. Low-lying Gulf and South Atlantic coastal counties are particularly vulnerable to storm surge. Most (56%) of the National Flood Insurance Program (NFIP) policies in force and 74% of total NFIP claim payments occurred in southeastern coastal counties between 1978 and 1998 (Heinz Center, 1999).

The increased costs in recent years has resulted more from increased property value and population intensity than from the frequency and intensity of storms (Pielke and Landsea, 1998). Future hurricane damages, projected from past storms, could average $5 billion per year (Pielke and Landsea, 1998). If climate change results in more frequent or more powerful storms, damages could conceivably be even higher.

Table 9.1 Billion Dollar Southeastern Weather Disasters, 1980-1999

(Source: National Climatic Data Center, 1999).

Disaster	Year	Estimated Damages/Costs*	Estimated Deaths**
AR/TN Tornadoes	1999	$ 1.3 billion	17
TX Flooding	1998	$ 1.0 billion	31
Hurricane Georges	1998	$ 5.9 billion	16
Hurricane Bonnie	1998	$ 1.0 billion	3
Southern Drought/Heat Wave	1998	$ 6.0-9.0 billion	200
El Nino/Tornadoes and floods	1998	$ 1.0 billion	132
MS/OH Valley Floods/Tornadoes	1997	$ 1.0 billion	67
Hurricane Fran	1996	$ 5.0 billion	37
Hurricane Opal	1995	$ 3.0 billion	27
TX/OK/LA/MS Severe Weather	1995	$ 5.0-6.0 billion	32
TX Flooding	1994	$ 1.0 billion	19
Tropical Storm Alberto	1994	$ 1.0 billion	32
Southeast Ice Storm	1994	$ 3.0 billion	9
Summer Drought/Heat Wave	1993	$ 1.0 billion	***
Hurricane Andrew	1992	$ 27.0 billion	58
Hurricane Bob	1991	$ 1.5 billion	18
TX/OK/LA/AR Flooding	1990	$ 1.0 billion	13
Hurricane Hugo	1989	$ 9.0 billion	57
Hurricane Juan	1985	$ 1.5 billion	63
Hurricane Elena	1985	$ 1.3 billion	4
Florida Freeze	1985	$ 1.2 billion	0
Florida Freeze	1983	$ 2.0 billion	0
Hurricane Alicia	1983	$ 3.0 billion	21
Total		$ 83.7-87.7 billion	856
** US only, *** undetermined			

Flooding is not the only problem stemming from climate anomalies in the Southeast. The southern heat wave and drought of 1998 resulted in damages in excess of $6 billion and at least 200 deaths. Also of concern in the Southeast are the effects that elevated surface temperatures have, as a result of prolonged or persistent periods of summertime heat events coupled with dry conditions, on human health. For example it is known that urban surface temperatures in cities in the Southeast can be elevated by as much as 3-5ºC (5-10ºF) over non-urbanized areas (Lo et al., 1997; Quattrochi and Luvall, 1999). These elevated urban surface temperatures are both a heat stress on humans and can also contribute to increasing both the duration and magnitude of ozone concentrations as discussed earlier (Southern Oxidant Study, 1995; Quattrochi, *et al*., 1998). Increases in maximum summer temperatures are of particular concern among lower income households that lack sufficient resources to improve insulation and install and operate air conditioning systems.

Understanding the risks and vulnerability of communities to weather-related hazards (considering hidden and reported costs and the actual frequency with which these disasters occur in the Southeast) is important to the quality of coping and mitigation strategies. Across the region, intense precipitation has increased over the past 100 years and some models suggest that this trend will continue as the atmosphere warms.

The possible impacts of short-term climate change (i.e., those resulting from the El Niño-Southern Oscillation) are the focus of this assessment. We next describe the potential impacts of ENSO on extreme weather events within the southeastern US.

9.2 Potential Impacts of Climate Change: ENSO and Extreme Weather Events

Due to anthropogenic origins or not, it has become of interest how the climate changes witnessed in the past 30 years will affect future weather and, in turn, its socioeconomic impact on human activity. One area of particular interest is the response of extreme weather events, such as hurricanes and tornadoes, due to the catastrophic damage they can produce. While the long-term implications of climate change on these phenomena are still unclear, short-term climate variability, on the time scale of months to a year, can give clues as to what the future can hold. This section focuses on the variability seen in US hurricane landfalls and tornadic activity related to climate anomalies and the ENSO cycle.

9.2.1 Climate Variability and Southeast US Hurricane Activity

At the present time, the principle means of relating hurricane activity to climate variables is through statistical regression models (Landsea, 2000). Perhaps the most well known of these techniques is the one employed by William Gray of Colorado State University. This model was first developed in 1984 (Gray, 1984) and has since been refined and improved upon (Gray, et al., 1993, 1994). Research by Gray and his colleagues have found that Atlantic hurricane activity can be significantly related to west African rainfall in the Sahel and the Gulf of Guinea (Landsea and Gray, 1992). Rainfall in this region during the months of August through November is employed by Gray to make his early (December) hurricane forecasts for the following season (Landsea, 2000). For the later forecast updates provided by Gray (June and August), knowledge about the state and progression of any ENSO activity is entered into the equation as well.

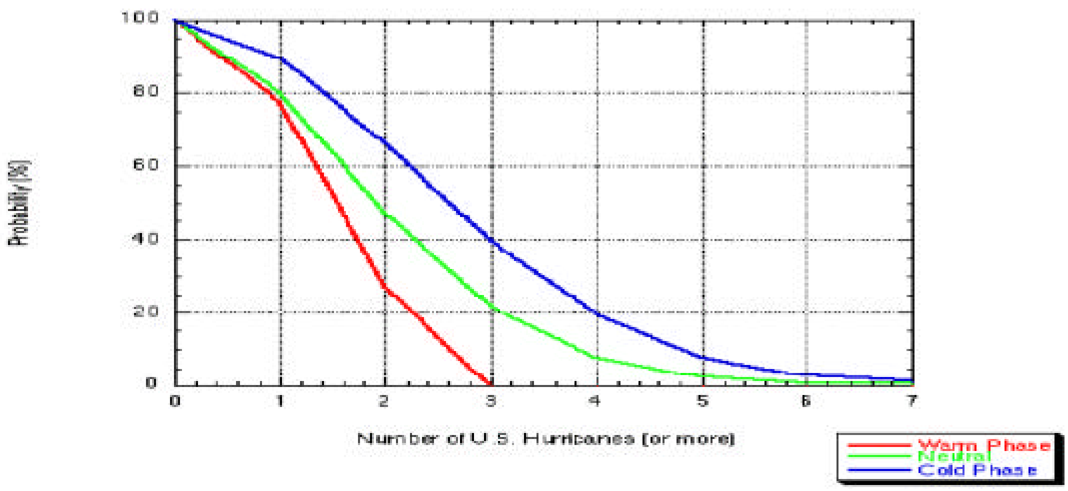
ENSO refers to the variability of sea surface temperatures and atmospheric pressure over the eastern tropical Pacific Ocean. The ENSO cycle has two extremes: El Niño (warm phase), which is an anomalous warming of the eastern tropical Pacific Ocean, and La Niña (cold phase), an anomalous cooling of the same region. This assessment is based on the definition of an El Niño event as developed by the Japan Meteorological Agency. The JMA Index defines El Niño events based on the sea surface temperature anomalies in the region 4° N to 4° S and 150° W to 90° W. An El Niño (La Niña) is identified when the five-month running average of SST anomalies is greater (less) than 0.5° C (-0.5° C) for at least six consecutive months. The event must begin before September and include October, November, and December. Years that do not meet the definition for either El Niño or La Nina are considered neutral (Bove et al, 1998).

Although a definite relationship between future climate change and the ENSO cycle has not been clearly identified, one model (Max-Planck Institute climate model, ECHAM4/OPYC3) simulates more frequent El Niño-like conditions and stronger La Niñas (Timmerman et al., 1999). These results are consistent with the Hadley model projections under a doubling of CO_2. The Max Planck Institute model is one of the few models with sufficient resolution in the tropics to adequately simulate narrow equatorial upwelling and low frequency waves. This model also suggests that the mean climate in the tropical Pacific region will shift toward a state corresponding to present-day El Niño conditions.

Accurate data for US hurricane landfalls exists from the year 1900. Over this time, there have been 22 El Niño years, 22 La Niña years, and 54 neutral years. In this assessment, a hurricane season is regarded as being influenced by El Niño (La Niña) if those conditions develop in the Pacific Ocean during the Atlantic hurricane season. From these years, the number of US hurricanes per ENSO phase is calculated. A tropical cyclone that makes at least one landfall somewhere in the U.S. as a hurricane, or affects a portion of the US coast with hurricane force winds, is considered a US hurricane. Under this definition, the mean annual number of U.S. hurricanes during El Niño years is 1.04, 1.61 during neutral years, and 2.23 during La Niña years (Bove et al., 1998).

A Poisson permissibility test, as described in Bove et al. (1998), is used to determine whether hurricane landfalls during each phase of the ENSO cycle can be described by a Poisson distribution. The test shows that neutral and cold events can be described by a Poisson process (Elsner and Schmertmann, 1993; Elsner and Kara, 2000). Warm events are not Poisson permissible, so an empirical approach is utilized. Using these two methods, we find the probability of two or more hurricanes making US landfall is 28% during El Niño, 48% during neutral years, and 66% during La Niña (Figure 9.1). Thus, one is almost three times as likely to see two hurricanes make landfall on the U.S. during La Niña than during El Niño. Further, the past 100 years of observations tell us that no more than two hurricanes have made U.S. landfalls during an El Niño year, while neutral and la Niña years have had as many as six US hurricane landfalls. Also, the chance of a major hurricane hitting the U.S. is decreased during El Niño and increased during La Niña (Bove et al., 1998).

Figure 9- 1. U.S. Hurricanes Cumulative Frequency



Besides affecting US landfalls, ENSO impacts the entire hurricane season as a whole. El Niño tends to produce unfavorable upper-level winds that inhibit thunderstorm growth, critical for hurricanes to develop. La Niña acts oppositely, producing favorable upper level winds that help thunderstorms grow, and allowing the hurricanes to develop. These unfavorable winds also influence the intensity the storms can reach, resulting in fewer major hurricanes (Gray, 1984).

9.2.2 Tornado Activity and ENSO

The tornado data record, unlike hurricane landfalls, only extends back to 1950. A simple analysis of this record was conducted by Bove (1997). These observed tornado occurrences, like the hurricanes, were classified as occurring during El Niño, La Niña, or neutral conditions. Each individual tornado event was sorted into 1.25° by 1.25° bins from 25° to 50° N and 75° to 110° W (the eastern two-thirds of the U.S.) and for which ENSO phase it occurred in. This technique is somewhat of an approximation since the length of every El Nino event is not the same, e.g., in some cases a tornado outbreak may have occurred after the El Nino was over (1998 for example), while in others the tornado activity may have occurred while a longer lasting El Nino event was still in progress (1983). Thus, grouping these two sets of conditions together represents a simplification of the actual climate dynamics.

However, accepting this simplification, the number of tornadoes in each bin during El Niño and La Niña events was compared to the number of tornadoes in the same bin during neutral conditions for statistical significance (Bove, 1997). Results were analyzed in three-month seasonal totals during the spring following the peak of an ENSO extreme event, when ENSO teleconnections are at their maximum influence on North America

The results indicate that there may be a decrease in tornadic activity over the southern plains (Texas, Oklahoma, Kansas,) during the spring following an El Niño year. Certain regions can see up to a 300% reduction in the number of tornadoes seen over the period (Figure 9.2). As shown in Figure 9.3, during the spring following a La Niña event, there is an apparent increase in the number of tornadoes seen in the Ohio River valley (Ohio, Indiana) and Deep South (Kentucky, Tennessee, Alabama). Areas of Tennessee and Indiana can see as much as a 300% increase in the usual amount of tornadoes for this region (Bove, 1997).

The confidence levels shown on Figures 9.2-9.3 must be considered as approximations only. In addition to the simplifications discussed above, this analysis also suffers from some statistical simplifications that make it difficult to determine the significance of the results. Two important ones are that observed monthly autocorrelations in tornado occurrences were not accounted for and no tests were done to

Figure 9.2. Statistically Significant Changes in Tornado Occurences
ENSO Warm - Neutral Event

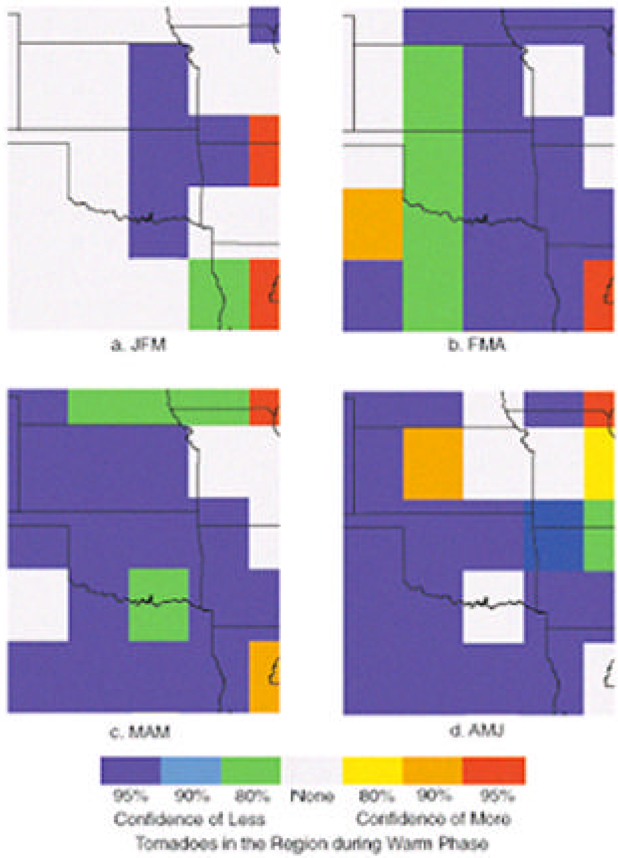
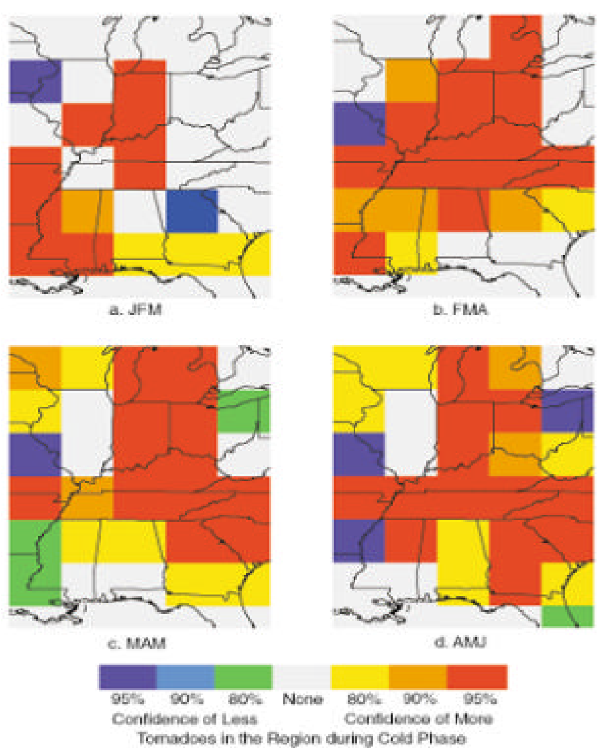


Figure 9.3 Statistically Significant Changes in Tornado Occurances
ENSO Cold - Neutral Event



determine if the data set contained outliers. The mean number of tornadoes in a season is a statistic that is very sensitive to the existence of outliers in the data. The existence of serial correlation and outliers in the data would both lead to overestimates of the significance of the results. Nevertheless, the results do tend to support the notion of a strong relationship between ENSO and tornado activity.

Further, El Niño and La Niña may also influence the size of outbreaks and intensity of tornadoes. A list of top 15 tornadic outbreaks with at least 40 tornadoes is obtained from Grazulis (1991). The date of each outbreak is used to determine the ENSO phase at the time. The results, shown in Table 9.2, reveal that only one outbreak out of the top 15 occurred during an El Niño event. Six of the top 15, including two of the top three, occurred during a La Niña event, while the remaining eight occurred during neutral ENSO years. This reveals that large outbreaks are indeed very scarce during El Niño events, and more common during non-El Niño years. Further, if one considers the fact that there are roughly twice as many neutral years than La Niña years, outbreaks during La Niña are also more common than in neutral years (Bove, 1997).

To test changes in intensity, annual F4 and F5 tornado data from 1950-1988 are taken from Grazulis (1991) and sorted by ENSO year (Table 9.3). La Niña years experience an average of 16.2 F4 and F5 tornadoes. Meanwhile, neutral and El Niño years only experience 8.42 and 8.2 F4 and F5 tornadoes, respectively. The data show that there is almost a doubling of the amount of devastating tornadoes during La Niña as compared to other years (Bove, 1997). Of course, the same caveats must be applied to these results as those discussed in the previous section due to the simplification of climate dynamics and statistical tests inherent in the analysis.

Table 9.2
15 Largest Tornado Outbreaks,1880-1990
relation to ENSO Events

Date	Total Tornadoes	ENSO Phase
1. Apr 3-4, 1974	148	Cold
2. Sep 19-23, 1967	111	Neutral
3. Mar 20-12, 1976	66	Cold
4. Jun 2-3, 1990	64	Neutral
5. Apr 2, 1982	61	Neutral
6. Mar 13, 1990	59	Neutral
7. May 8, 1988	57	Warm
8. May 25-26, 1965	51	Cold
9. May 4-5, 1959	49	Neutral
10. Apr 11-12, 1965	48	Cold
11. Jan 9-10, 1975	47	Cold
12. May 15-16, 1968	46	Cold
13. Apr 21, 1967	45	Neutral
14. Jun 7-8, 1984	45	Neutral
15. May 29, 1980	44	Neutral

Source: Grazulis 19

Table 9.3
Occurrences of F4 and F5 Tornadoes
With Respect to ENSO Event, 1950-1988

ENSO Event	# of Events	Total F4-F5 Tornadoes	Amount per Year
Cold	10	162	16.2
Neutral	19	146	8.42
Warm	10	82	8.2

Data Source: Grazulis 1991

The changes in tornado patterns are a result of the large-scale atmospheric patterns over the U.S. During El Niño, the subtropical jet stream is intensified while the northern jet stream is weakened. This results in weaker cold fronts moving south from Canada, and less moist air being drawn up from the Gulf of Mexico. With weaker dynamics and temperature gradients, the conditions needed for tornadoes are not met as often.

Meanwhile, La Niña intensifies the northern jet stream and shifts it southeastward, while the subtropical jet is weakened. This allows for stronger cold fronts to move south into the U.S., and this brings up more warm moist air from the Gulf of Mexico. Thus, the dynamics and temperature gradients are enhanced, allowing for tornado development, but east of where they are normally expected (Bove, 1997).

9.3 Summary of ENSO and Extreme Weather Findings

Global change will influence these two types of extreme climate events, but to what extent can not be readily determined. For example, warmer ocean waters might create more hurricanes, but a warmer atmosphere aloft might weaken them. Also, warmer water might create more El Niño events, which would in turn reduce hurricane and tornado activity within the region. Thus, it is hard to determine what role climate change will play on these events. While the relationship between climate change and extreme weather events is uncertain, increases in coastal populations, infrastructure, and development suggest that even small growth in storm frequency or severity could create a disproportionate increase in damage.

Chapter 10

Adaptation/Coping options

An important component of the National Assessment process is the identification of specific strategies that may help the region or sector cope with the anticipated consequences of changes in both short-term and longer term climate. These strategies are considered as opportunities for “win-win” or “no regrets” responses that take into consideration the potential effects of climate variability and change in the context of current environmental and socioeconomic stresses. In this section, some of these adaptation options are summarized for each sector studied in the Southeast region. This list of options is not meant to be exhaustive, but rather it is illustrative of the possibilities that may exist to lessen impacts resulting from variations in future climate.

10.1 Agriculture

A combination of technological advances and adaptive management practices could minimize potential adverse effects and amplify the potential positive effects of climate change on agricultural productivity in the Southeast. For example, selection of soybean varieties with a higher temperature tolerance could potentially maintain current yields if future temperature increases by 2ºC or so. Changes in planting date may also benefit soybean yield if future temperature increases. Management strategies or technological advances that would improve water availability or plant water use efficiency may help offset potential loss in productivity resulting from increased temperatures and reduced levels of precipitation. Other strategies, such as a shift to crops optimal for the new climate, might also be considered. Understanding the cyclical El

Niño and La Niña influences on the climate of the region has many potential benefits for agriculture. Farmers can adjust planting dates, species or varieties cultivated, harvest schedules, and many other aspects of their annual operations with advanced knowledge of likely weather conditions based on the ENSO phases (Legler et al., 1999).

10.2 Forests

It is not economically practical to intensively manage all 200 million acres of southern US timberland. The intensity of forest management varies across regions and forest types and is usually a function of timber value. Annually, 1.8 billion seedlings are planted within the southern region. These planted trees provide an opportunity to alter forest response to climate change through improved genetic engineering. Improvements in disease resistance, drought tolerance, and bark thickness may allow forests within the region to better withstand future stress (Shultz 1997). This type of coping strategy could benefit forest productivity regardless of climate change and is currently an important component of timber industry research.

On less economically valuable lands, management of the forest to increase drought or fire tolerance could be accomplished by altering the forest harvest practice (e.g., group-cut v. individual tree selection) that favor regeneration of desired species. The use of prescribed burning and forest thinning could be employed to reduce drought stress and the potential for catastrophic fire.

Another coping strategy would be to increase forest rotation length to maximize carbon sequestration. The economic value of the additional forest growth does not usually offset the opportunity cost of cutting the tree with a shorter rotation and then reinvesting the funds from the cutting. To make lengthening the forest rotation economically (and therefore practically) viable, carbon credits in the form of tax breaks or other compensation could be considered (van Kooten et al., 1995).

In general, southeastern forest productivity will likely be enhanced by atmospheric carbon enrichment, as long as precipitation does not decline or air temperature increase soil moisture stress to a level that would offset potential CO_2 benefits on productivity. Potential coping and mitigation strategies include genetic and silvicultural system improvements that could increase water use efficiency or soil water availability. The knowledge of the role of fire, hurricanes, droughts and other natural disturbances will be important in developing forest management regimes and increases in stand productivity that are sustainable over the long term. Timber productivity associated with increased temperature, growing season length and carbon enrichment may be further enhanced by improved genetic selection, bio-engineering, use of marginal agricultural land for tree production, and more intensive forest management. Reduction of air pollutants (e. g., ozone, nitrous oxide) could also be an important strategy for increasing forest productivity.

10.3 Water Quality

There are several coping strategies (“win-win” actions) that can have substantial benefits even if climate changes are gradual and minimal or do not occur at all. In the broadest sense, improvements in watershed management making them more integrated and comprehensive can reduce flood and drought damages and can protect water quality in streams, rivers, lakes and reservoirs, and groundwater. The reduction of effluents such as nitrates to the southeastern streams can also reduce the impacts of climate-related changes in streamflow. Coping strategies in this area include improved agricultural and forest practices that reduce the use of critical resources such as nutrients, pesticides, and water. The maintenance of adequate riparian zones especially in areas where major animal management operations are located is another cost-effective strategy that can help to protect watersheds and streams in the Southeast and sustain ecosystem health.

10.4 Air Quality

Since air quality impacts related to ground-level ozone are associated with photochemical reactions involving oxygen, nitrogen oxides (NO_x), volatile organic compounds (VOC) from incomplete combustion and natural biogenic sources, and ultraviolet radiation, the coping strategies, for the most part, involve the reduction of emissions. More efficient use of energy resources in the transportation and industrial sectors especially can reduce the emissions of the major ozone precursors (NO_x and VOC). A more sophisticated system for predicting extreme ozone days using meteorological conditions would also be useful so that control strategies could be implemented when needed and on a more site-specific basis. With the appropriate analytical tools, state and local air pollution agencies could test and develop cost-effective ozone control strategies.

10.5 Extreme Weather Events

Understanding the risks and vulnerability of communities to weather-related hazards (considering hidden and reported costs and the actual frequency with which these disasters occur in the Southeast) is important to the quality of coping and mitigation strategies. Across the region, intense precipitation has increased over the past 100 years and some models suggest that this trend will continue as the atmosphere warms. Traditional mitigation strategies such as flood proofing, elevated structures, and building codes, are no longer adequate in themselves, particularly in the coastal zone. Even if storms do not increase in frequency or intensity, sea-level rise alone will increase the propensity for storm surge flooding in virtually all Southeast coastal areas.

The National Oceanic and Atmospheric Administration (NOAA) and the Federal Emergency Management Agency (FEMA) commissioned a study on the true costs and mitigation of coastal hazards in 1996. Their report calls for a paradigm shift in hazard mitigation and focuses on model state programs developed in Florida and others parts of the country to foster more disaster-resilient communities. Recommendations include improvements in disaster cost accounting and risk assessment, insurance/mitigation policy linkages, integrated approaches to coastal management/development, and community-based mitigation planning (Heinz Center, 1999). Changes in climate and sea-level rise should be an integral consideration as Southeast coastal communities develop strategies for hazard preparedness and mitigation.

IV. PLANNING FOR THE 21st CENTURY

Chapter 11

Critical Unknowns and Research Needs

An important feature of the National Assessment process is the identification of critical unknowns and research questions that need to be addressed in the future. This first climate impact assessment like those initiated in other regions of the country was driven both by a tight time schedule and by funding limitations. Each region focused on a few critical issues and sectors identified through a scoping workshop process. In each case, the resulting analysis of potential impacts and benefits of climate change was limited and should be considered as a first-cut assessment. In this section some of the questions and issues are identified by sector that need to be evaluated in any subsequent assessment of the southeastern US. Again, the list is not exhaustive, but it does represent the assessment team's perspective on future research needs.

11.1 Agriculture

The southeastern US has a very productive agricultural sector that produces many high value crops, such as citrus, vegetables, and several field crops. Diversity in production is accompanied by equally diverse cropping and farming systems, including animal systems, aquaculture, diseases, insects, and weeds. This current assessment of the consequences of climate on agriculture in the Southeast focused only on several important row crops including corn, cotton, peanuts, rice, sorghum, soybeans, and winter wheat. In the future, it will therefore be important to include the impacts and benefits of climate variations on other high value crops (citrus and vegetables) and on animal management practices.

The role of climate on pests and pest management systems also needs to be included in future assessments. It will also be necessary to develop, validate, and evaluate new technological capabilities such as new genetic varieties that will help farmers cope with any changes in future climate. The effects of biotechnology (i.e., transgenic crops) on future agricultural productivity in this region including the benefits of using less fertilizer, pesticides, or water need to be evaluated in light of different climate regimes. Because the incorporation of new climate-related technological capabilities into agriculture is relatively new and yet unproven, future pilot studies should be identified to explore the communication and transfer of information to and within the stakeholder community.

11.2 Forests

Although many basic physiological relationships between climate change and plant growth have been addressed since the inception of the national global change research program in the early 1990s, there is very limited understanding of the interactions between stress on individual trees, especially on multiple environmental stress interactions at the forest, landscape, or regional level. Specific examples of gaps in our understanding of ecosystem processes include: (1) the interaction between atmospheric CO_2, and soil water and nutrient limitations on forest productivity, carbon sequestration and species composition; (2) the interactions between CO_2 and tropospheric

O_3 on plant water use efficiency; (3) the migration rates of tree species under climate change; (4) the rate of ecosystem establishment under climate change; and (5) improved integration of forest process models used to predict future conditions at multiple spatial scales.

In addition to increased understanding of the mechanisms associated with climate change impacts on forests, improved and enhanced emphasis needs to be placed on long-term monitoring of forest composition and growth. These databases are critical to accurately develop the baseline from which future scenarios are calculated, and for use in validating model prediction of historic and current conditions. A combination of permanent ground-based forest monitoring plots and improved remote sensing technologies could be instrumental in characterizing future US forests.

11.3 Land Use Change

One limitation of our modeling approach is the imbalance of information on climate-related economic effects in the forest and agricultural sector. While the land model integrates directly with the SRTS model, no link to agricultural commodity markets exists. Therefore, while reallocation of land between forests and agriculture does affect the simulated timber prices, any effect on agricultural prices remain undetected. This model shortcoming may not be too problematic if agricultural prices for the southeastern US are largely determined by national and global commodity markets. However, if the land transfers are substantial enough, some effect on commodity prices seems likely. Thus further integration of the forest, agricultural, and land sectors may be warranted. These inter-sectoral linkages have been modeled at the national level by Adams et al. (1996).

Another limitation to consider is the narrow focus of our analysis on one region. While this has allowed for a more detailed examination of intra-regional phenomena, it ignores the effect that climate impacts elsewhere might have on the region. Nowhere is this more relevant than in commodity production and land use. As described herein, differences across regions in forest and agricultural impacts could have a substantial effect on the southeastern US's comparative advantage in the relevant commodity markets. This, in turn could have a more important impact on how land is allocated than on the relative impacts on forests and agriculture within the region that are modeled here.

11.4 Water Quality

If precipitation patterns continue to change on a scale that is similar to that observed over the past 100 years, many southeastern aquatic ecosystems, including estuaries, will be affected by changes in streamflow. There are several unknown variables corresponding to future conditions that might affect water quality in the southeastern US. They fall into two major categories: future pollutant loadings (natural and anthropogenic) and biophysical reactions. The pollutant loadings, both point and non-point, will be directly related to changes in land use activity including the presence of confined animal systems and growing population centers. Also, atmospheric deposition of nitrogen will be tied to emissions of nitrogen oxides (NO_x) from combustion sources. The biophysical reactions on the land surface that might serve to uptake nitrogen and other constituents will be associated with land cover conversion and vegetation. Future research programs that include these two critical unknowns seem crucial to gaining a clearer understanding of the relationship between variations in climate and water quality in the Southeast.

The BASINS software includes the permitted effluent discharge data by stream reach for each HUC and a database is currently being constructed by EPA on future population projections and land use changes by county for 2000-2100. These data can be used in conjunction with the approach used in the Southeast Regional Assessment to examine future water quality conditions in greater detail.

The results of the first phase of the assessment have demonstrated the troublesome nature of the response on the Gulf Coast over the next 30 years or so.   For this reason, an area on the Alabama Gulf Coast (Baldwin County) has been selected for intensive study in the second phase. Baldwin County, AL is located contiguous to Mobile Bay and is one of the most productive agricultural counties in the state. At the same time their has been a significant influx of population moving from the Mobile area over to the county. It is felt that these land use demographics, in conjunction with the projected impacts of climate change, make this county a prime area for intensive study.

Another intensive study site will be selected in the Mississippi delta region as well. It has been determined that agricultural productivity in this area is also particularly sensitive to climate variability. A battery of sensitivity studies, including historical climate-agricultural yield relationships, water availability, and crop yield will be run for the selected site.

Quantitative data describing the response of native southeastern plant communities to atmospheric carbon enrichment, water quality (e. g., salinity) and changes in temperature and soil moisture are limited to a few key species. Moreover, very few studies have addressed the potential interactions among climate variables and between plant species, and even fewer studies deal with climate effects at secondary and higher levels in the food web. A more detailed study of the effects of climate change on freshwater ecology in southeastern streams is also warranted.

11.5 Air Quality

Air quality is a major concern of urban areas and because it contributes to a host of environmental and human health problems (e.g., chronic and acute respiratory diseases). The cost of compliance of specific air pollution regulations, such as for ozone, can exceed billions of dollars regionally, and tens of billions of dollars nationally (NRC, 1991). Special emphasis should be placed on pollutants, such as ground-level ozone, that are affected by temperature and thus are likely affected by climate variability and change. The influence of meteorological fluctuations and ambient ozone concentrations is not fully understood because of the lack of data and credible analytical tools. Therefore, efforts must continue to improve the performance of various statistical models used to forecast maximum daily ozone concentrations in response to varying climatic factors. Air quality regulatory programs are in need of better ozone-predicting methods so the opportunity to find the best-performing statistical model is a priority.

In addition, future air quality assessments need to consider emission profiles from both anthropogenic (i.e., coal-fired powerplants and transportation sources) and biogenic sources that are allowed to change over time in response to growing populations and air quality regulations. The ultimate tool for forecasting ozone will likely be a combination of a real-time photochemical model and a statistical meteorological model.

To evaluate the potential for harmful health effects from air pollution, future assessments will also need to better correlate changes in air quality, especially maximum levels of ground-level ozone, to toxicological studies, human clinical studies, and epidemiological studies. Since any human disease is multifactoral in nature, these future studies will benefit from a clearer definition of the role of climatic factors in conjunction with the other biological and social factors.

11.6 Extreme Weather Events

Changes in disturbance patterns (e.g., hurricanes, floods, drought, fire) are possibly more significant in terms of potential economic losses than longer-term changes in precipitation and temperature. Ecosystems are also impacted by climate-related disturbances. Disturbance is a natural process that, in many cases, not only structures ecosystems but also sustains them as well. Our limited understanding of the role of disturbance in natural ecosystems and our inability to predict climate extremes hinders those interested in mitigating the potential adverse impacts of climate change.

Existing general circulation models cannot adequately resolve some components of climate or certain geographic or topographic features that are important because of their interaction with regional climate features. For coastal regions, much uncertainty exists relative to the effects of climate change and variability on tropical storms, the most important natural hazard affecting regional vulnerability. Effects of climate change on area of hurricane origination and threshold for hurricane formation, intensity, frequency, and tracks are poorly understood and will require future investigation.

11.7 Additional Issues

Six additional climate-related issues were identified for the Southeast region. These are topics that should be included in any future assessment of the region. They include the following:

11.7.1 Water Resources: Fresh water plays an important role in many sectors including coastal resources, health, agriculture, estuarine fisheries, and forestry. Competing demands for already stressed groundwater systems, such as urban development, agriculture and recreation could be exacerbated by changes in precipitation and salt water intrusion from sea-level rise.

11.7.2 Impacts on Coastal Ecosystems and Services: Sea-level rise, changes in fresh water delivery to coastal estuaries, and increased atmospheric temperature and CO_2 all can lead to changes in the structure and function of coastal and estuarine systems. Losses of coastal marshes and submerged aquatic vegetation will have impacts at higher trophic levels. Gulf Coast states currently produce most of the Nation's shrimp, oysters and crabs, and each of these estuarine fisheries are dependent upon the primary productivity of coastal ecosystems. Changes in fresh water flow resulting from new precipitation patterns can significantly affect estuarine productivity.

11.7.3 Health Issues related to Water Quality: The effects on surface waters of changes in precipitation have important health implications in the region. Increased precipitation promotes the transportation of bacteria as well as other pathogens and contaminants by surface waters throughout the region. Health consequences may range from shellfish infections transmitted to humans to ground water contamination associated with salt water intrusion.

11.7.4 Socioeconomic and Insurance Issues: In the ultimate analysis, the issue of climate change and the need for an assessment of potential consequences will be relevant to the degree that it is placed on a human scale. To this end, the societal impacts of climate change must be identified and understood. Insurance exposure and/or the insurability of coastal and island facilities are issues that should be examined in the context of climate change and variability.

11.7.5 Urban Issues: A distinctive characteristic of southeastern coastal regions is their current high level of urbanization and rate of population growth, which could be affected by changes in climate that are considered in this assessment. The urban environment will have its own responses to the impacts of climate change and variability. While responses will be driven by stakeholder and policymaker decisions, they need to be evaluated and understood within the framework of different potential regional scenarios of climate change consequences. Design and construction factors, building code issues, infrastructure and lifelines, urban heat islands, energy use, structural vulnerability to natural hazards, land use and zoning issues, traffic patterns, and evacuation/shelter infrastructure are all important areas for potential mitigation and future research.

11.7.6 Climate model limitations: The Southeast is the only region for which current climate models simulate large and opposing changes in precipitation patterns over the next 100 years. The range of differences is so great that it is difficult to state with any degree of confidence that precipitation will increase or decrease in the Southeast over the next 30 to 100 years as atmospheric CO_2 and other greenhouse gases increase. Until climate models are improved or until there is a way to validate and compare the accuracy of current models, people in this region must consider a wide range of potential future changes in soil moisture and runoff, as was assumed in this regional assessment.

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Appendix A

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